The Structure of Energy Demand in Australia: an Econometric Investigation with Some Economic Applications

by

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Declaration

Except where otherwise indicated this thesis contains my own work

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To Ammi Ji and Abba Ji

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List of Acronyms

ABARE	*Australian Bureau of Agricultural and Resource Economics*
ABS	*Australian Bureau of Statistics*
ACT	*Australian Capital Territory*
ADO	*Automotive Diesel Oil*
AGA	*Australian Gas Association*
AI	*Almost Ideal*
AREM	*Autoregressive Error Model*
CDD	*Cooling Degree-Days*
CDE	*Constant Difference Elasticity*
CES	*Constant Elasticity of Substitution*
CH_4	*Methane*
CO_2	*Carbon Dioxide*
CO_2-*e*	*Carbon Dioxide Equivalent*
CPI	*Consumer Price Index*
DF	*Degrees of Freedom*
DOLS	*Dynamic Ordinary Least Squares*
DW	*Durbin-Watson*
DWL	*Deadweight Loss*
E-G-W	*Electricity, Gas and Water*
ESAA	*Electricity Supply Association of Australia*
EV	*Equivalent Variation*
FOC	*First Order Conditions*
GDP	*Gross Domestic Product*
GHG	*Greenhouse gases*
GNP	*Gross National Product*
GWP	*Global Warming Potential*
HDD	*Heating Degree-Days*
IDF	*Industrial Diesel Fuels*
IPCC	*Inter-governmental Panel on Climate Change*
LES	*Linear Expenditure System*
LR	*Likelihood Ratio*
MJ	*Million Joules*
ML	*Maximum Likelihood*
Mt	*Million tonnes*
N_2O	*Nitrous Oxide*
N_2O	*Nitrous Oxide*
NGGIC	*National Greenhouse Gas Inventory Committee*
NRCF	*Normalised Restricted Cost Function*
NSW	*New South Wales*
NT	*Northern Territory*
OECD	*Organisation for Cooperation and Development*
PFC	*Perfluorocarbons*
PIGLOG	*Price Independent Generalised Logarithmic*
PJ	*Peta Joule*
QLD	*Queensland*
SA	*South Australia*
SM	*Slutsky Matrix*
TAS	*Tasmania*
UK	*United Kingdom*
UNFCCC	*United Nations Framework Convention on Climate Change*
US	*United States*
VECM	*Vector Error Correction Model*
VIC	*Victoria*
WA	*Western Australia*

General Notes

Units

Kilo	10^3
Mega	10^6
Giga	10^9
Tera	10^{12}
Peta	10^{15}
Exa	10^{18}

Symbols used in tables

..	*Not available*
na	*Not applicable*
-	*Zero*

Notes

- *The analysis in this document employs fiscal years unless otherwise specified. The year 1998, for instance, covers the period from July 1997 to June 1998.*
- *Dollars are Australian unless otherwise specified.*

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Abstract

The literature on the estimation of energy demand in Australia is reviewed and the need to obtain fresh estimates of energy demand parameters is highlighted. After illuminating trends in national energy consumption, its mix and greenhouse gas emissions in Chapter 2, the structure of consumer energy demand is modelled in Chapter 3 using the Almost Ideal demand system, with dynamic representations, and time series data. In Chapter 4 the dynamic OLS is applied to estimate, again, the consumer energy demand in an attempt to get a second opinion on the inter-fuel substitution relationships, as the statistical evidence in the previous chapter tends to favour complementarity in the electricity and gas use. The chapter, using the estimated demand structures, also projects residential energy consumption and greenhouse gas emissions under baseline conditions and a carbon tax scenario. The next chapter assesses the impact of the tax on welfare by computing the deadweight loss.

Chapter 6 models the inter-fuel substitution structure of the Australian commercial and industrial sectors by dividing the two sectors into 37 industries and categorising energy employed into electricity, gas, oil and coal. Using a dynamic factor demands model, the next chapter endogenises the demand for aggregate energy, along with other factor aggregates and fuel sources. Chapter 8 integrates the estimates of the energy demand structure estimated in different chapters with a view to identifying energy substitution possibilities in various industries/sectors. Generally, industries are characterised by very inelastic energy demand and limited substitution opportunities between different energy sources. Chapter 9 summarises the thesis and discusses briefly the contributions and weaknesses of the research undertaken.

1

Introduction

Synopsis

The literature on greenhouse mitigation costs in Australia and the estimation of energy demand, including energy substitution with other factors/commodities and inter-fuel substitutions, is reviewed. The role of energy demand parameters in the large-scale economic models designed to investigate climate change issues is analysed. The limitations of the existing empirical literature on energy demand are discussed and the need to obtain fresh estimates of energy demand parameters is highlighted. Methodologies for modelling consumer and industrial and commercial energy demands are chosen and briefly discussed. The chapter ends with an outline of the thesis.

1.1 Introduction

Half a century ago, Professor Hendrik S. Houthakker wrote an article on urban electricity demand in the United Kingdom (UK) which sparked interest in the econometric investigation of energy demand (Houthakker 1951). More than two decades later, interest in the subject rose sharply due to the oil price shocks of the 1970s. As a consequence of this phenomenon, and the availability of flexible functional forms developed largely during the 1970s, a huge body of literature on the subject emerged during the 1970s and 1980s. A favourite topic in these studies was analysis of the nature of the relationship between energy and other factors, especially capital, in the production processes of various economies, with a focus on the industrialised nations (see, for instance, Hudson and Jorgenson 1974; Berndt and Wood 1975; Pindyck 1979; Turnovsky *et al.* 1982; Truong 1985).

Rising environmental concerns at the approach of the new millenium have given a new dimension to this interest. The emission of carbon dioxide, CO_2, and other greenhouse gases (GHG) into the atmosphere and the associated threat of climate change have become sensitive issues worldwide. This is a matter of particular significance in Australia, as it is the world's 17th largest emitter of GHG in terms of overall emissions and the fourth largest emitter on a per capita basis. Vast resources of primary energy, especially of coal, and a relatively small population are the main reasons why Australia is behind only three nations in terms of per capita emissions.

Nearly four-fifths of total GHG emissions in Australia are associated with the energy sector, which comprises stationary energy, transport and fugitive-fuel (NGGIC 2000b:11).[1] Energy sector emissions, in turn, are dominated by stationary energy emissions consisting primarily of those related to electricity generation. Roughly three-quarters of the additional GHG emissions between 1990 and 1998, for instance, were due solely to the stationary energy sector which is dominated by the power generation sector (NGGIC 2000b:11). In Australia electricity is generated mostly from coal, which has a higher carbon content than most of the competing fuels. In 1999, for example, approximately 84 per cent of electricity was generated from coal (ESAA 2000). Australia has vast resources of coal, which are generally conveniently located and the solid fuel is relatively cheap. These factors give coal an edge over the other fuels as far as power generation is concerned.

The intertwined issues of energy demand and climate change have attracted considerable attention in Australia, which is hardly surprising given energy's crucial role in the fabric of the Australian economy. The economics literature on the subject has mainly focussed on studying the economic impacts of reducing the anthropogenic greenhouse gas emissions. Quite understandably, this research has principally been carried out using models of the global economy or of the Australian economy, like that of most other industrialised nations.

In the Kyoto Protocol, Australia has committed to constraining its GHG emissions to 8 per cent above their 1990 level in the first commitment period, 2008-2012. In order to achieve this target, Australia may have to cut GHG emissions by approximately 22 per cent in 2010 relative to the business-as-usual emissions in 2010 (Brown *et al.* 1999:5). Most of this abatement in emissions is expected to be achieved through energy demand management – energy conservation, and switching from more carbon-intensive to less carbon-intensive fuels. A thorough understanding of energy use behaviour, therefore, is of crucial significance.

The available literature on the estimation of energy demand in Australia – fuel substitutions with other factor aggregates/commodities and inter-fuel substitutions – is not only scant, but also emerged predominantly in the distant past, from the 1960s to the mid-1980s. To the best of this author's knowledge, only a single article on the topic was published during the 1990s, analysing factor substitution possibilities between energy and other factor inputs in the electricity supply industry of South Australia (Rushdi 1991). The estimates of the energy demand structure in the studies conducted in the 1970s and 1980s have limited relevance today, as fuel prices, especially of the petroleum products, behaved very differently during the late 1980s and in the 1990s as compared with the corresponding price movements during the 1970s and early 1980s (Madlener 1996:4).

More importantly, in recent years energy demand has been modelled using dynamic demand systems and other modern dynamic econometric methods, such as error correction and cointegration analysis (Clements and Madlener1999; Ramanathan 1999; Considine 2000). The Australian literature on energy demand estimation, on the other hand, is based on static demand systems and single equation techniques with static and dynamic formulations – an approach that has been severely criticised in the literature on energy demand estimation (Berndt *et al.* 1981:261-72; Norsworthy and Harper 1981:178-9). Furthermore, to the best of this author's knowledge, not a single study is available on the residential sector, analysing inter-fuel substitution possibilities in a comprehensive fashion.

The main aim of this research has been to fill this empirical gap. More precisely, this study specifies and estimates the interrelated demand for various energy sources with a view to obtaining a comprehensive set of energy demand parameters characterising energy use behaviour in different sectors, including the residential, industrial and commercial sectors. This research also investigates the impacts of imposing a carbon tax, which is designed to mitigate GHG emissions, on welfare and on consumer energy demand and the associated GHG emissions. Also, the estimated energy demand structures are investigated thoroughly to pinpoint the energy conservation potential, including inter-fuel substitution opportunities, in different sectors/industries.

The remainder of this introductory chapter is organised as follows: Section 1.2 reviews a selection of the available literature on the costs of greenhouse gas mitigation. The importance of the estimation of energy demand elasticities is briefly highlighted in Section 1.3. The Australian literature reporting energy demand estimations is reviewed in Section 1.4, which also includes a discussion on the limitations of the existing energy demand studies. The methodologies proposed for modelling energy demand in the various sectors are briefly described in Section 1.5, and, finally, a brief outline of the thesis is given in Section 1.6.

1.2 Greenhouse gas mitigation cost studies – a review

Three papers – McKibbin and Pearce (1996), McDoughall and Dixon (1996) and Common and Hamilton (1996) – focus on examining the consequences for the Australian economy of a unilateral carbon tax designed to reduce greenhouse gas emissions. To this end, McKibbin and Pearce (1996) employ the G-Cubed model. The G-Cubed model, which is a dynamic general equilibrium model of the world economy, divides the global economy into eight regions (Table 1.1). Australia is distinguished as one of the regions, which are linked by trade and capital flows. Each region, in turn, comprises a representative household, a government sector, a financial sector, 12 industries and two capital-producing sectors. Producers in each region choose between different factor inputs – labour, capital, energy and materials – and investment in order to maximise its stock market value subject to the constant elasticity of substitution (CES) technology. Energy demand, in turn, is a CES aggregate of five energy sources and material inputs are also a CES aggregate of various intermediate products. The model is estimated econometrically using mainly United States' (US) time-series data and the resulting substitution elasticities are also applied to the other regions.

Results from simulating the model show that a carbon tax that reduces the CO_2 emissions in 2005 to the 1990 level results, if imposed smoothly, in a cumulative GNP loss of $55 billion (in 1994 dollars) between 1990 and 2005.[2] The cost of the tax increases substantially, by approximately 24 per cent, if imposed immediately without smoothing.

The authors also consider two alternative tax scenarios: one in which all OECD countries stabilise their emissions at 1990 levels; and a second in which all countries stabilise, separately, their emissions at 1990 levels by introducing carbon taxes. The cumulative GNP loss under the OECD stabilisation case increases to $56 billion and to $58 billion under the worldwide carbon tax regime. The relatively large GNP loss in the last scenario is largely due a dramatic reduction in Australian coal exports. On the basis of these findings, the authors tend not to favour an Australian unilateral carbon tax, as it is expected to be very costly in terms of incomes forgone without, however, a noticeable reduction in world CO_2 emissions.

McDougall and Dixon (1996) use the ORANI-E model – a comparative static, general equilibrium model of the Australian economy – to investigate the economic impacts on the Australian economy of a unilateral carbon tax. The ORANI-E model, which is derived from ORANI to analyse energy-related issues, specifies the production structure of more than 120 industries. The household sector, reflected by a representative household, owns factors of production and government is supposed to maintain a neutral fiscal position by adjusting income taxes. The model allows for energy-capital substitution, substitution between different energy sources, and substitution between different technologies in the electricity generation sector.

The study uses a tax on fuels that is based on the energy content and not on the carbon content. The authors, however, note that changes in *ad valorem* terms would be very similar had the tax been applied on the carbon content. Broadly speaking, the study performs two types of simulations. First, the energy tax is recycled in the form of a payroll tax deduction. In the second scenario, the tax revenue is used to reduce the government budget deficit. GDP and employment are estimated to rise while the general price level falls in the first set of simulations. The direction of change in the above variables is exactly the opposite when the energy tax revenue is used to reduce the government budget deficit.

The way the carbon/energy tax is used largely explains the difference in results from the above two studies. The G-Cubed model uses the carbon tax revenue to reduce the fiscal deficit, whereas in McDougall and Dixon (1996), the tax revenue, in one set of experiments, is used to reduce the distortionery payroll tax, and, in the other set, the tax revenue is used to reduce the government budget deficit. Common and Hamilton (1996) review the simulations performed in the above studies, especially the projected impacts on economic growth and employment, and conclude that there is a *prima facie* case for a unilateral Australian carbon tax if the tax revenue is used appropriately.

Table 1.1 **Mitigation cost studies**

Study	Model	Region	Year	CO_2 Reduction[!] (per cent)	Output Loss[!] (per cent)	
					GNP	GDP
Common & Hamilton (1996)	G-Cubed	Global, eight regions	2004	16	..	0.62
Dickson *et el.* (1996)	MENSA	Country (Australia)	..	stabilisation at 2000 level	..	\$1.8 billion[a]
			..	40 per cent below 2000 baseline[b]	..	\$93.6 billion[a]
			..	40 per cent below 2000 baseline[c]	..	\$54.7 billion[a]
McDougall & Dixon (1996)	ORANI-E	Country (Australia)	..	4.6 to 11.8	..	0.09 to -0.20
McKibbin & Pearce (1996)	G-Cubed	Global, eight regions	2005	34 (UA)	0.89	0.99
McKibbin *et al.* (1998)	G-Cubed	Global, eight regions	2010	20 (IA)	2.5	0.1
			2010	13.1 (PT)	2	0.1
Brown *et al.* (1999)	GTEM	Global, 18 regions	2010	22 (IA)	0.65	..
			2010	15 (PT)	0.50	..
McKibbin *et al.* (1999)	G-Cubed	Global, eight regions	2010	42.2 (IA)	2.2	2.6
			2010	21.8 (PT)	1.5	1.5

Notes: !- relative to the baseline emissions or GNP/GDP for the year. a- the abatement cost over the period 1990-2020 discounted to \$1990 at the 8 per cent discount rate, b- nuclear power is not considered as an option, c- nuclear power is treated as an option. IA = independent abatement, PT = permit trading, UA = unilateral abatement.

The Bureau of Industry Economics (1996) employed the ORANI-E model to estimate the economic effects of energy efficiency improvements across various industries – the so-called 'no regrets' opportunities that exist due to market failures and distortions. The study puts a great deal of effort into quantifying the potential energy efficiency gains for various industries, which range from 0.5 per cent in the electricity, gas and water sector to 7.3 per cent in mining.[3] According to the simulation results, the potential energy efficiency gains are estimated to increase GDP by around 0.33 per cent in the long-run. Interestingly, owing to this income rise and increased consumption, nearly three-quarters of the initial CO_2 savings from the 'no regrets' energy efficiency improvements in different industries are mitigated in the long-run.

With a view to analysing the implications of meeting greenhouse targets in Australia on the energy sector and, specifically, on coal consumption, Dickson *et al.* (1996) use a bottom-up or engineering-based modelling approach. The authors employ the Australian Bureau of Agricultural and Resource Economics' MENSA model – a large multiperiod linear programming model of the Australian energy sector. Very briefly, given the economic and technical characteristics of a comprehensive range of energy extraction, conversion and end-use technologies, MENSA determines the least-cost way of satisfying exogenously-specified time paths for energy demands by households and industries outside the energy sector. In the electricity generation sector, the model considers, along with the traditional generation technologies, more advanced technologies having high thermal efficiency and also nuclear power.

The authors perform a number of simulations apart from baseline projections – which involve no greenhouse gas constraints – for the period 1990 to 2020. In the first set, which contains two experiments, nuclear power is excluded as an option on the energy supply side. In the first experiment, the CO_2 emissions are stabilised at the baseline 2000 levels from year 2000 onwards. In the other case, the CO_2 emissions are reduced in 5 per cent steps from 2000 onwards until a 40 per cent reduction in emissions is achieved. In the year 2000 stabilisation case, the additional cost of satisfying the exogenously given energy demand between 2000 and 2020 is estimated at $1.8 billion (in present value terms using 1990 dollars). The cost increases to $94 billion in the other simulation, which is understandable, as the model has to choose from more expensive technologies, including more expensive gas and coal technologies as specified in the model.

The two simulations from the other set are exactly the same, except that the nuclear option is reinstated. The corresponding additional costs (again in present value terms) are $0.8 billion and $55 billion, respectively, for the stabilisation and the 40 per cent reduction scenarios. The nuclear option, thus, is estimated to result in significant cost savings. The results, the authors note, should be taken with caution, as the model does not specify energy demands and the macro-economic effects of greenhouse gas reductions.

Recently McKibbin *et al.* (1998) and Brown *et al.* (1999), using economic models of the global economy, have investigated the implications of meeting the Kyoto Protocol. McKibbin *et al.* (1998) use the G-Cubed model to examine the effects of the tradeable emissions permit system proposed in the 1997 Kyoto Protocol. The researchers perform a number of experiments to explore the effects of the Protocol under different assumptions about the extent of permit trading, three of which are considered here. In the first simulation, the 'Annex I' countries – essentially OECD economies plus countries of the former Soviet Union – meet their commitments independently without permit trading. The second scenario involves the same set of countries but allows international permit trading among the Annex I countries. The final case involves global permit trading, as developing regions are allocated permits that are consistent with their baseline emission projections.

In the first scenario, the permit price for Australia during 2010 is \$57 per tonne of carbon, the lowest among the OECD regions. The GNP loss relative to the baseline case, in contrast, is the highest in the OECD regions; GNP is estimated to be 2.5 per cent lower in 2010 and 4.6 per cent lower in 2020 – the last period for which the model is solved. In the second scenario, the common permit price in the OECD countries increases from \$37 per tonne of carbon in 2010 to \$77 per tonne of carbon in 2020, implying that Australia will be a net permit buyer. The GNP loss in this case is slightly lower – 2 per cent lower in 2010 and 4.1 per cent lower in 2020, relative to the baseline figures.

When the developing regions are brought into the picture, the marginal abatement cost and permit price fall sharply to \$13 per tonne of carbon abated for the year 2010 and to \$23 per tonne of carbon for the last year, 2020. The Australian economy, like many other industrialised nations, benefits from markedly lower permit prices, which is evident from the fact that GNP for the year 2020 is only 1.3 per cent lower than the baseline GNP.

Brown *et al.* (1999) employ a dynamic general equilibrium model of the world economy, GTEM – global model of trade and environment. The GTEM version used in this study divides the global economy into 18 regions (see Table 1.1). Australia is distinguished as one of the regions, with 23 industries producing tradeable goods in a perfectly competitive environment using constant returns to scale technologies. The regions are linked through capital flows with investment demands determined by changes in the regional GDP and the relative expected rates of return. In the energy intensive industries – electricity generation and the iron and steel industry – producers are able to substitute between different technologies. In other industries, the model allows substitution not only between different energy sources but also between energy and the primary factor aggregates. The model accounts for three greenhouse gases: CO_2

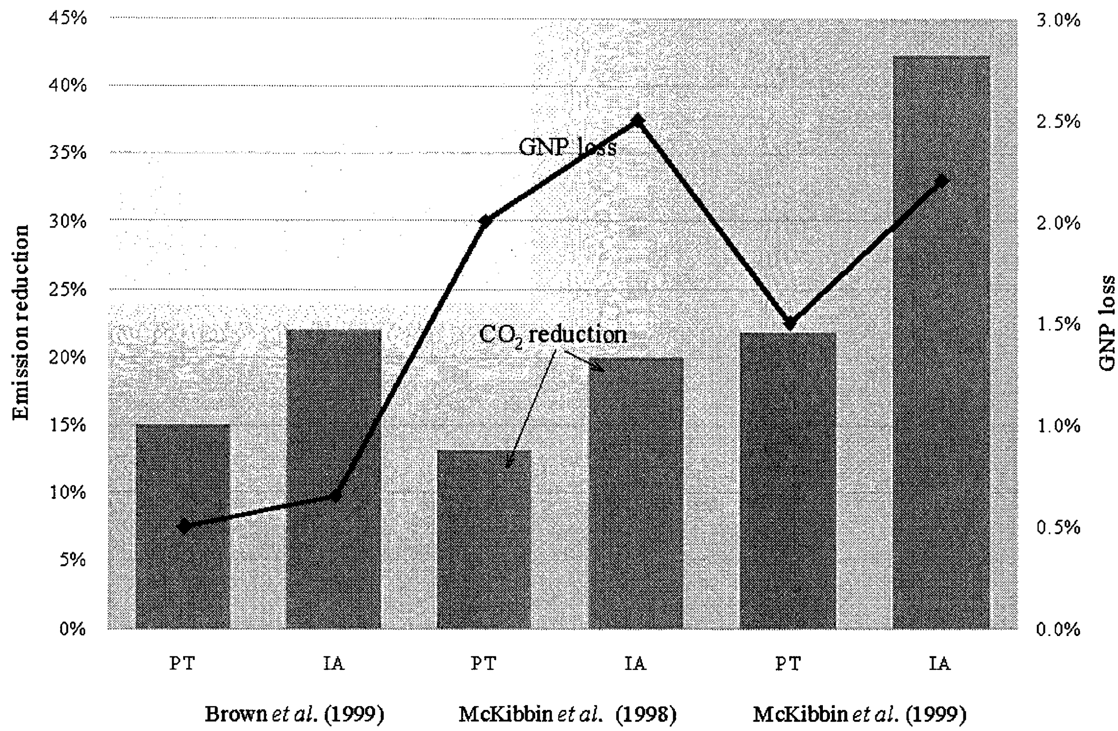
from combustion and other sources, methane and nitrous oxide – a feature that distinguishes it from most other models of the world economy, as they typically only include CO_2 from combustion sources.

In the baseline scenario, the Australian CO_2 equivalent emissions are estimated to grow at an average rate of 1.65 per cent per annum between 1990 and 2010. For Australia, under the independent abatement scenario, a carbon tax of US$200 per tonne of carbon, in 1992 dollars, during 2010 is required to meet the target, which leads to more than half a per cent GDP loss in 2010 relative to the corresponding business-as-usual GDP for the year (see Table 1.1 and Figure 1.1). Both the GDP loss and the carbon tax penalty are lower if emissions trading among the Annex I countries is introduced. The global GNP loss under the independent scheme, relative to the business-as-usual case is nearly 0.8 per cent in 2010, and falls to less than 0.2 per cent under the emissions trading scheme.

In a similar exercise, McKibbin *et al.* (1999), again using the G-Cubed model, examine the impact on the OECD economies of introducing an OECD-only system of internationally tradeable emissions permits to stabilise the OECD CO_2 emissions at the level of 1990. The authors analyse three scenarios: (1) unilateral emissions stabilisation by the US; (2) OECD emissions stabilisation without emissions trading; and (3) OECD emissions stabilisation while permitting permit trading within the OECD regions. In the second scenario, in which the OECD countries stabilise emissions without permit trading, Australia is shown to be hurt substantially more than the other three regions; GDP falls below baseline GDP by 2.6 per cent in 2010 and 2.2 per cent in 2020, primarily due to higher abatement costs and lower coal exports to Japan.

The permit price per tonne of carbon for Australia is estimated to increase from US$219 in 2010 to US$248 in the year 2020. The corresponding prices for the US and Japan are lower, especially for the US, but higher for the other OECD region. Under the scenario of emissions trading, the US is shown to be a significant supplier of emission permits due to its lower marginal abatement costs. The common permit price increases from $116 in 2010 to $132 in 2020. As expected, the GDP loss for Australia is relatively small – GDP is 1.5 per cent lower in relation to the business-as-usual situation, both in 2010 and 2020.

Figure 1.1 **Emission reduction and GNP loss** (per cent)



Note: IA = independent abatement, PT = permit trading.

1.3 Implications for energy demand estimation

However, results from these models vary substantially, implying a current lack of consensus about emission abatement costs. Interestingly, substantial differences persist across models, even after harmonising crucial exogenous variables. EMF (1993) [reviewed in IPCC 1996:304-9], for example, employed 14 different economic models, mostly global in terms of coverage, to analyse a standardised set of emission reduction scenarios for the US economy. The study attempted to compute taxes per tonne of carbon required to meet various CO_2 emission reduction targets. In order to enhance understanding of the sources of differences across models, common assumptions regarding GDP and population growth, the fossil fuel resource base, and the cost and availability of long-run supply options were employed.

Despite the standardisation, results across models varied greatly. In one of the simulations, in which the study sought to determine the carbon taxes needed to stabilize CO_2 emissions in 2000 at the 1990 level, the tax per tonne of carbon for the year 2000 varied from US$20 to US$150 across the models. Similarly, the estimates of carbon taxes required to reduce emissions by 20 per cent below 1990 levels in 2010 ranged from US$50 to US$300 per tonne of carbon.

Two sets of parameters – energy demand elasticities and the parameters characterising capital stock adjustment to higher energy prices – are particularly crucial in explaining the differentials in results across models (IPCC 1996:307). Typically, in these large-scale models, these parameters correspond to simple and quite often restrictive technologies. The G-Cubed and the GTEM models, for instance, employ the CES production function, which imposes the same substitution elasticity across all inputs and thus rules out the possibility of complementarity. Furthermore, typically the parameters used in these models are not estimated econometrically, due largely to the huge data requirements. Rather, in many instances, the modelers assume these parameters. It is worth mentioning that the G-Cubed is not a fully econometrically-estimated model, as the parameters characterising the producer behaviour are estimated using only US data and the resulting substitution elasticities are applied to the other seven regions included in the model.

During the coming decade or so, the emissions reduction burden is likely to fall mostly on the demand side of the energy sector. The supply side is expected to remain constrained over this period, as the probability of obtaining an alternative energy source which is relatively environment friendly and reasonably abundant at competitive prices, is not very high. A fuller understanding of energy use behaviour, especially knowledge of the inter-fuel substitution elasticities, is, therefore, vital.

Surprisingly, the estimation of energy demand elasticities for different sectors has not attracted a great deal of attention in Australia, especially in more recent years. Almost all available studies on this subject were conducted during the late 1970s and early 1980s, following the two energy shocks of the 1970s. To the best of this author's knowledge, just a single article on the estimation of energy demand elasticities for Australia was published during the 1990s (Rushdi 1991). In the following pages the studies on the estimation of the energy demand elasticities are reviewed.[4]

1.4 Energy demand studies – a survey

For the purposes of this review, the literature on energy demand elasticities is divided into two categories: the papers involving single equation methods based on an *ad hoc* approach are treated as one group and reviewed first. The research based on simultaneous equation methods or a systems approach is summarised afterwards.

1.4.1 Single equation models

Most of the research belonging to the first category was conducted during the late 1970s or the early 1980s. The focus of concern, in this period, was electricity demand – residential and non-residential. Hawkins (1975), for example, studied the demand for electricity at the retail level for the residential, commercial and industrial sectors using cross-section data from New South Wales (NSW) and the Australian Capital Territory (ACT). Residential electricity demand is represented by a system comprising two equations. The first equation formulates the electricity demand per electricity customer as a function of income, fuel prices and demographic and geographical variables.[5] The other equation attempts to explain the proportion of electricity customers who have a gas connection with the help of availability of gas supplies, the cost of acquiring a gas connection, income and prices of other fuels.

Two formulations for the industrial and commercial sectors are adopted. The first specification expresses average electricity consumption as a function of the sectoral activity level, the price of electricity and prices of other factors of production, including those of labour and capital. In the other formulation, the average electricity demand is regressed on electricity price and quantities of labour and capital.

According to the estimation results, residential electricity demand is price inelastic – own-price elasticity equals -0.55 – and nearly unit elasticity with respect to income (Table 1.2). The proportion of households with gas is almost solely explained by the availability of gas. The study, on the other hand, finds little evidence that the commercial and industrial electricity demand is fuel price responsive, although it is found to be sensitive to the level of economic activity.

Donnelly and Saddler (1984), in their attempt to explain retail electricity demand in Tasmania, combine electricity demand across residential, agricultural, commercial and industrial users. Using time-series data from 1961 to 1980 and a log-linear functional form, the authors express electricity demand as a function of real electricity and heating oil prices, real income and a temperature variable. The own-price elasticity of -0.56 is very similar to that of Hawkins' (1975) estimate of the residential sector electricity demand elasticity for NSW and the ACT. Also, electricity and heating oils are significant substitutes, according to the regression results (Table 1.2).

Donnelly (1984) conducted a similar exercise for the ACT. Using annual time-series data from 1964 to 1982, Donnelly specified residential electricity use as a function of the electricity price, the price of substitute fuels, income and the weather which is represented by the heating and cooling degree-days. The study employs the stock adjustment model to account for the fixity of electricity appliances. Based on the double-log specification, the long-run own and cross-price elasticities are -0.77 and 0.42, respectively; and the corresponding estimate of the income elasticity is 0.69. The linear specification, also attempted in the study, gives fairly similar results.

In another paper, Donnelly and Diesendorf (1985) use various variable elasticity models to estimate the residential electricity demand function for the ACT employing the time-series data set used in Donnelly (1984). The own-price elasticity of the fuel falls almost consistently across different models from more than unity in 1964 to less than one in 1982. The elasticity estimates at the means, across different models, are very similar (Table 1.2).

Donnelly (1982) models the demand for petrol by state with a view to computing both short and long-run price and income responses. The dependence of petrol demand on the stock of motor vehicles is modelled indirectly due to the non-availability of adequate data on the stock of motor vehicles. More precisely, the author uses the stock adjustment model to incorporate adjustment. The study uses quarterly data from the third quarter 1958 to the second quarter 1981 on a panel of six states namely New South Wales (NSW), Victoria (VIC), Queensland (QLD), South Australia (SA), Western Australia (WA) and Tasmania (TAS). The seemingly unrelated iterative regression procedure of Zellner is followed to pool the time-series cross-section data. The OLS estimates for each of the six states are also obtained.

In comparison with the OLS estimates, the Zellner estimates show relatively less price responsive but comparatively income responsive petrol demand. The long-run price elasticity in the case of OLS, for instance, varies between -0.48 (NSW) and -1.52 (TAS). According to the Zellner estimator, the price elasticity is estimated to vary between -0.35 (NSW) and -0.89 (TAS). On the other hand, the OLS version of the long-run income elasticity varies between 0.34 (TAS) and 0.81 (QLD). According to the Zellner estimates, the long-run income elasticity varies between 0.55 (TAS) and 0.88 (QLD). The petrol demand responses, both short and long-run, are fairly similar in NSW and Victoria, so much so the null hypothesis of identical demand parameters in both states is not rejected.

Stromback (1986), in his attempt to model aggregate electricity demand for Western Australia, adopted a different approach. Electricity demand is expressed as a product of a utilisation rate and the stock of energy using appliances, measured in the units of electricity.[6] Both the utilisation rate and the optimal capital stock variables are assumed to be dynamic functions of real electricity price and the real employment income in

Western Australia. The study, using quarterly data from 1964 to 1982, finds a very slow adjustment in electricity demand in response to both income and price variations.

Table 1.2 **Single equation based energy demand studies**

Author	Functional Form	Data	Region	User/Fuel	Elasticity
Hawkins (1975)	linear, static	cross section, 1971	NSW, ACT	Residential (electricity)	ε_{11}^{LR} = -0.55, η_{1Y}^{LR} = 0.93, (evaluated at the means)
Donnelly (1981)	log-linear, dynamic	panel, 1958.3 – 1981.2	NSW, VIC, QLD, SA, WA, TAS	Combined (petrol)	ε_{33}^{SR} =-0.11, ε_{33}^{LR} =-0.30 to -0.69 η_{3Y}^{SR} =0.09 to 0.26, η_{3Y}^{LR} =0.57 to 0.87
Donnelly (1982)	Log-linear, dynamic	panel, 1958.3 – 1981.2	NSW, VIC, QLD, SA, WA, TAS	Combined (petrol)	ε_{33}^{SR} = -0.09 to -0.18, ε_{33}^{LR} =-0.35 to -1.52, η_{3Y}^{SR} = 0.04 to 0.29, η_{3Y}^{LR} = 0.34 to 0.88
Donnelly (1984)	log-linear dynamic	annual time series, 1964-82	ACT	Residential (electricity)	ε_{11}^{SR} = -0.35, ε_{11}^{LR} =-0.77, ε_{13}^{SR} = 0.19, ε_{13}^{LR} = 0.42, η_{1Y}^{SR} = 0.31, η_{1Y}^{LR} = 0.69
//	linear, dynamic	//	//	//	ε_{11}^{SR} = -0.33, ε_{11}^{LR} =-0.86, ε_{13}^{SR} = 0.17, ε_{13}^{LR} = 0.46, η_{1Y}^{SR} = 0.12, η_{1Y}^{LR} = 0.32, (evaluated at the means)
Donnelly and Saddler (1984)	log-linear, static	annual time series 1961-80	TAS	Retail users (electricity)	ε_{11}^{LR} = -0.56, ε_{13}^{LR} = 0.31, η_{1Y}^{LR} = 1.13
Donnelly & Diesendorf (1985)	several specifi-cations	annual time series, 1964-82	ACT	Residential (electricity)	ε_{11}^{LR} = -0.76 to -0.81 (evaluated at the means)

Note: ACT= Australian Capital Territory, NSW = New South Wales, VIC= Victoria, SA = South Australia, WA = Western Australia, TAS = Tasmania. 1 = electricity, 3 = petroleum products, SR = short-run, LR = long-run, ε_{ij} = demand elasticity of ith fuel source with respect to jth fuel's price and η_{iY} = demand elasticity of ith fuel source with respect to income.

1.4.2 System-based studies

The system based demand studies are even less common, especially for the residential sector, for which apparently only one paper has been published. Rushdi (1986), using a translog demand system and annual time-series data from 1960 to 1982, modelled the interrelated demand for electricity, gas and oil by the residential sector of South Australia. The demand for electricity is price inelastic and the elasticity estimate is fairly close to the corresponding estimates reported in Donnelly (1984). The demand for the other two fuels, by contrast, is price elastic. Furthermore, electricity is a substitute for the other two fuels. Gas and oil, in contrast, are consumed in a complementary fashion (see Table 1.3).

Relatively greater attention has been paid to studying the energy substitution possibilities in the industrial and commercial sectors. Again, most of the research was conducted in the late 1970s and early 1980s. Duncan and Binswanger (1976), using national-level, annual time-series data spanning the period 1949 to 1967, investigated energy substitution possibilities and factor efficiency biases in Australian manufacturing. The manufacturing sector was divided into 16 industries. The unit energy cost function for each industry was approximated by a translog function, linearly homogenous, comprising five fuels – coal, fuel oil, electricity, coal gas and a residual fuel – and a time trend to capture the impact of technical progress. As the objective of the research was to study the inter-fuel substitution possibilities and fuel efficiency biases in the manufacturing industries, the study did not consider the aggregate model.

However, the inter-fuel demand elasticities and factor efficiency bias results are reported for only five industries due to the rejection of the linear homogeneity and symmetry restrictions in most industries. Some of the reported own-price elasticities are positively signed, indicating concavity violations in those five industries.

Technical progress is electricity-using in all five industries but coal-saving in most industries. The fuel efficiency bias is not quite obvious in the case of the other three fuels, as the respective coefficients change sign across industries and/or are insignificant. Electricity demand is least elastic of all fuels, whereas fuel oil demand varies markedly across the five industries. Fuel oil and coal are substitutes while electricity and fuel oil are complementary fuels in most industries.

Hawkins (1977) estimated the demand functions for six factors in 10 major energy consuming manufacturing industries, including three energy sources – solid fuels, liquid fuels and electricity and gas. The factor demand equations were derived subject to the constant difference elasticity of substitution production function, developed by Hanoch (1975). For the purposes of estimation, a dynamic structure using the Koyck adjustment process was added. A corresponding unrestricted dynamic model, for each industry, was also formulated as a base case. The study covers the period from 1950 to 1968, that is

19 years. The estimation results are not very encouraging; price variables are largely insignificant and wrongly signed, with a significant t-score in many instances. In the case of the factor demand models that correspond to the CDE function, the conditions implied by the production function are constantly rejected. The author tests for temporal stability of the estimated functions and finds unstable equations in most industries. The factor demand functions are, as a result, estimated by dividing the period into two roughly equal sub-periods. There is, however, no improvement in results.

In another paper, Hawkins (1978) employs a vintage model of demand to investigate the demand for labour input among three energy sources, including solid fuels, liquid fuels and electricity and gas. The model is applied to annual time series data covering 57 manufacturing industries, which are pooled into five groups, depending on the energy intensity of production and the ratio of electricity to total energy consumption. This method of aggregation across industries, the author says, is chosen with a view to maximising 'between groups' variation relative to 'within group' variation.

The vintage model is applied to each of the five groups and ex-ante elasticities are computed. Out of the 15 own-price elasticities of fuel demand, six are wrongly signed, though not all significant. The own-price elasticities vary considerably across industry groups, from as low as -0.04 (solid fuels) to -1.37 (electricity and gas). While solid and liquid fuels are substitutes in four industry groups, there is no dominant relationship in the case of other fuel pairs.

Turnovsky *et al.* (1982) study the production structure of aggregate manufacturing by using the two-stage optimisation procedure suggested by Fuss (1977). Using the dual approach, the authors represent the aggregate cost structure by a homothetic translog model specified in terms of capital, labour, materials and energy. The unit energy cost function is specified in terms of solid fuels, oil, electricity and gas. The two models are implemented using annual time-series data from 1947 to 1975.

Unlike most time-series data based studies of factor substitution, Turnovsky *et al.* (1982) find substitutability between capital and energy and complementarity between labour and energy (Table 1.3). For the fuel submodel, the study finds complementarity between solid fuels-gas and oil-gas; all other fuel pairs are substitutes. Although the overall energy demand is fairly price insensitive – aggregate energy demand elasticity equals -0.22 – the inter-fuel substitution elasticities show considerable price sensitivity. For instance, the estimated own-price elasticity of gas, holding total energy demand constant, is -1.45.

Table 1.3 **System-based energy demand studies**

Author	Functional specification	Data	Sector	Main results
Duncan and Binswanger (1976)	static translog (fuel model only)	annual time series, 1949-67	five manufacturing industries	Technical Progress • electricity using • coal-saving in three industries • not very obvious in other cases elasticities • electricity demand least elastic • fuel oil elasticity varies considerably • fuel oil-coal substitutes • electricity-fuel oil complements in most cases.
Hawkins (1977)	constant difference elasticity of substitution	annual time series, 1950-68	ten manufacturing industries	• conditions implied by the production theory are rejected • price variables are largely insignificant.
Hawkins (1978)	vintage model	annual time series, 1949-68	manufacturing industries	• curvature violations • solid and liquid fuels substitutes in most cases • no obvious pattern in the cases of other fuel pairs • fuels: solid fuels, liquid fuels and electricity and gas
Turnovsky *et al.* (1982)	static translog	annual time series, 1947-75	manufacturing	Aggregate model • substitutes: K-L, K-E, K-M, L-M, E-M • complements: L-E fuel model • substitutes: S-O, S-El, O-G, El-G • complements: S-G, O-El
Rushdi (1984)	static translog	annual time-series, 1969-80	aggregate manufacturing and 12 manufacturing industries (SA)	El, G & O are substitutes in aggregate manufacturing and the demand for El is least elastic of all fuel
Turnovsky & Donnelly (1984)	static translog	annual time series, 1947-79	iron & steel	Aggregate model • substitutes: K-L, K-E, L-E, L-M, E-M • complements: K-M fuel model • substitutes: S-O, S-El, O-El, El-G • complements: S-G, O-G
Truong (1985)	Rotterdam model	annual time-series, 1969-81	manufacturing (NSW)	Aggregate model • all factors are substitutes with the exception of capital and energy fuel choice model • complements: El-G, El-Lf, S-G, S-Of • substitutes: E-Of, E-S, S-Lf, Lf-G, Lf-Of, G-Of

Rushdi (1986)	static translog	annual time series, 1960-82	residential sector (SA)	• substitutes: electricity-gas, electricity-oil • complements: gas-oil • electricity demand inelastic • gas and oil demand elastic
Rushdi (1991)	static translog	annual time-series, 1950-84	electricity supply industry (SA)	Complements: K-L, L-E Substitutes: K-E

Notes: 1- Turnovsky and Donnelly (1984) considered different combinations of factor aggregates in their econometric estimation of the aggregate cost function. However, in this table results from a four-factor model are mentioned. 2. K = capital, L = labour, E = energy, M = materials, S = solid fuels, Lf = liquid fuels, El = electricity, G = gas, O = oil, Of= other fuels.

In another paper, Turnovsky and Donnelly (1984) investigate the energy substitution possibilities in the Australian iron and steel industry using the two-stage optimisation procedure mentioned above. The paper uses linearly homogenous translog specifications to approximate both the aggregate cost function and the unit energy cost function. Both models are estimated using annual time-series data from 1960 to 1979. A distinguishing feature of this study is that it divides labour input into administrative labour and production labour and finds that total labour does not form a consistent aggregate. The authors test various weak separability hypotheses and find materials weakly separable from the other three factor aggregates – capital, labour and energy. Based on national-level annual time-series data from 1960 to 1979, capital and energy are substitutes, whereas production labour and energy are complements. The largest sample considered in the paper, 1947 to 1979, finds complementarity between capital and energy for the 1950s and the 1960s but substitutability for the 1970s. As far as the energy submodel is concerned, solid fuels-gas and oil-gas are substitutes (Table 1.3).

Using both single-equation and system methods and time-series data, Rushdi (1984) investigates the industrial demand for energy, including electricity, gas and oil, in South Australia. Total industrial demand for electricity in the state, which is estimated using single-equation specification with static and dynamic formulations, is assumed to depend on the prices of electricity and oil, industrial output and a time trend among others. While the reported price elasticities across the formulations are fairly similar, the output elasticity is twice as large in the dynamic model.

The author also models the demand for electricity, gas and oil in South Australian manufacturing using the translog model and time-series data from 1969 to 1980. The translog cost function, along with fuel cost shares, are estimated for aggregate manufacturing as well as for 12 manufacturing industries. The demand for electricity is least price responsive, whereas that of gas is the most price sensitive across industries with, however, a few exceptions. In the case of aggregate manufacturing, the three fuels are substitutes. However, in individual industries complementarity in fuel consumption is found in some cases although the three fuels are predominantly substitutes.

Truong (1985) employs the absolute version of the Rotterdam model to analyse inter-fuel and inter-factor substitution possibilities in New South Wales manufacturing. The aggregate model is specified in terms of labour, capital, materials and energy. The fuel choice model includes five fuels: electricity, gas, solid fuels, liquid fuels and other fuels. Both the aggregate choice and the fuel choice models are estimated using time-series data from 1969 to 1981.

The demand for capital is most price responsive of all factors with own-price elasticity of -0.72. This is followed by energy (-0.45), labour (-0.37) and materials (-0.15). Capital and energy are complements whereas other factor pairs are substitutes. The demand for various fuels is even more own-price responsive; the own-price elasticities of fuel inputs range from -1.1 (liquid fuels) to -0.35 (electricity). As far as the inter-fuel relationships are concerned, electricity-solid fuels, electricity-liquid fuels, solid fuels-gas and solid fuels-other fuels are complements whereas the remaining fuel pairs are substitutes.

In another paper, Rushdi (1991) specifies a non-homothetic translog cost function to estimate economies of scale and factor substitutions in the electricity supply industry of South Australia. The cost function, specified in terms of capital, labour, energy, output and load factor, is estimated using time-series data from 1950 to 1984 for one utility – the Electricity Trust Board of South Australia. The author reports four different sets of demand parameters, depending on the depreciation rate assumed and real interest rate. The own-price elasticity of energy for the electricity supply industry is estimated to vary between -0.19 and -0.31. Capital-labour and labour-energy are complements, whereas capital-energy are substitutes. Furthermore, significant scale economies are found in the industry; a 1 per cent increase in electricity production is likely to increase total costs by a little more than 0.5 per cent.

1.4.3 Limitations of the existing studies

As is obvious from the above review of literature on energy demand elasticities in Australia, the estimated demand structures contain limited usefulness in today's circumstances, primarily because most of this research was conducted using data from the 1960s to the mid-1980s. The energy price behaviour during the last 15 years has been different from that during the 1970s and early 1980s. The period from the mid-

1980s onwards is characterised by stable to declining real energy prices, whereas during the 1970s and early 1980s real energy prices, especially those of petroleum products, rose sharply, triggered by the two oil shocks of the 1970s.

Furthermore, most of this research was conducted using energy demand models – commodity or input demand – whose appropriateness in terms of approximating the underlying energy demand structure in a reasonably satisfactory manner, has been seriously questioned in the literature on energy demand modelling. A significant number of studies, for instance, modelled electricity demand using single equation methods. In some cases, dynamics were added to the estimating equation by introducing stock adjustment type formulations. In other cases, the long-term price and income elasticities of electricity demand were computed from the static single-equation specifications.

It has long been acknowledged that following a shock economic agents are unable to adjust energy demand, or for that matter demand for other factor inputs/commodities, instantaneously to the long-run equilibrium levels. Energy demand in the short-run is determined in large part by the technical features of the energy-using equipment in place, and an energy price increase, in most cases, is expected to change the utilisation rate of the equipment. The long-run response to an energy price shock is constrained in part by the rate at which the energy using capital is replaced (Berndt *et al.* 1981:260).

However, the stock adjustment model in the context of a single equation model is not an appropriate approximation of the underlying adjustment process. A simple example should make this clear. Imagine that a firm is combining labour, capital, materials and energy in a least cost manner to produce a given level of output. Assume further that the energy price increases, leaving the firm out of equilibrium. Immediately after the shock, in an effort to minimise costs in the changed environment, the firm will attempt to substitute labour and materials for the energy-capital bundle (assuming substitutes) as energy and capital are employed in roughly fixed proportions in the short-run. However, as a part of the long-run response to the shock, the firm will probably try to replace the existing capital with more energy efficient equipment. In short, a shock is expected to result in a generalised disequilibrium, not just disequilibrium in the energy market.

Apart from imposing strong restrictions on the short and long-run responses, a single equation stock adjustment model is bound to misrepresent the underlying adjustment process.[7] Berndt *et al.* (1981:262) even cast doubt on the interpretation of the estimated parameters as elasticities, because the partial adjustment specification is not explicitly based on economic optimisation.

Most other studies included in this review have taken into consideration that energy demand is determined in an interdependent framework. These studies, however, have employed static models, implying that factor demands, including energy and capital, adjust instantaneously in response to price and output variations. Turnovsky *et al.* (1982), for instance, implicitly assume that there exists a steady state cost function characterising the manufacturing industry, such that each input bundle included in the sample represents an equilibrium production technology fully adjusted to current prices and output. Taken literally, it implies that in response to, for example, an energy price shock, the quantity of physical capital will adjust completely over a period of one year. This seems to be a very strong assumption given the body of literature suggesting that physical capital adjustment faces steeply rising adjustment costs.

Furthermore, as Norsworthy and Harper (1981:179) argue, a relative price change sets in motion two types of factor substitution processes: short and long-run. The long-run substitution is triggered by the changed price environment. The short-run substitution between different factors, in contrast, takes place to account for the stickiness of some factor inputs, such as capital. More flexible factors are substituted for the relatively stickier inputs such as physical capital, to minimise costs. As the static models consider only the long-run substitutions, the ignored short-run dynamics, Norsworthy and Harper argue, may contaminate the long-run picture.

1.5 Methodology

As mentioned above, the main objective of this research has been to model energy demand by the residential, industrial and commercial sectors in Australia with a view to obtaining a comprehensive set of energy demand elasticities. The study employs the interrelated factor/commodity demand models, as energy demand by economic agents – households and firms – is not determined in an isolated setup. More importantly, the aim is to do this in a dynamic framework which explicitly recognises the interdependent nature of the disequilibrium process.

Several dynamic models of factor demands have been developed to analyse energy demand. Nadiri and Rosen (1969, 1973), for example, suggested a generalised version of the single-equation partial adjustment mechanism, involving systems of interrelated disequilibrium equations. This kind of generalised adjustment scheme permits disequilibrium in one factor market to influence the demand for the other factors, allowing for short-run overshooting possibilities. A principal drawback of this approach lies in the fact that dynamics are introduced in an *ad hoc* fashion and do not explicitly take into account the dynamic optimising behaviour of economic theory.

Lau (1976) and McFadden (1978) developed another approach which is also capable of characterising both short and long-run demand behaviours. Essentially, in this approach, a short-run cost function is specified and the corresponding short-run variable demand functions are obtained by applying the Shephard's lemma.[8] The demand for the variable factor inputs depends on (variable) factor prices and on the quantities of output and fixed factor(s). The important link between the average short-run cost curves and the corresponding long-run average cost function is utilised to obtain the long-run responses. The approach can be combined with various cost functions but it works especially well with the quadratic specification, as this function greatly facilitates the analytic derivation of the fixed factor demand functions (Berndt *et al.* 1981:271). As the model is based on static optimisation methods, it is unable to characterise the adjustment path towards a steady state equilibrium following a shock. However, as noted above, such information is of crucial significance in economic models designed to study greenhouse gas mitigation costs.

Anderson and Blundell (1982, 1983, 1984) parameterised a static demand system as a vector error correction model (VECM) to introduce dynamics in the context of both input and commodity demand systems. The VECM nests within it Nadiri and Rosen's (1969) partial adjustment model and the static model with autoregressive errors.[9] However, in this model the parameters associated with the lagged variables are not identified, although the steady state parameters are identified. Recently, Allen and Urga (1999) have derived a cost function capable of generating Anderson and Blundell-type dynamic demand systems. In so doing, they also solved the parametric identification problem faced by Anderson and Blundell.

Berndt *et al.* (1980), on the other hand, developed a dynamic factor demands model that is explicitly based on dynamic economic optimisation principles and characterises completely both short and long-run demand. Capital stock, a quasi-fixed factor input in this model, is subject to increasing marginal adjustment costs, assumed to result from internal disruptions within the firm.[10] Relying on Treadway's (1974) work on the partial adjustment/flexible accelerator, they employ an explicit solution for the optimal investment problem. This, in turn, requires them to represent the underlying production structure by a restricted variable quadratic cost function, in addition to assuming that producers have static expectations regarding factor and output prices.[11]

Pindyck and Rotemberg (1983) also proposed a dynamic system of factor demands that employs rational expectations regarding the evolution of output and input prices and is also explicitly based on dynamic optimisation principles in the presence of quadratic adjustment costs for the quasi-fixed factors, capital and labour. Their estimated model provides a complete description of the short-run and the long-run elasticities. They were, however, unable to calculate optimal factor demand trajectories due to the complexity of the underlying control problem which led them to perform simulations in a deterministic context to compute factor input responses to changes in factor prices.

This study employs the dynamic specification suggested by Berndt *et al.* (1980), as it completely summarises the time path to the steady state equilibrium. Two features of this approach are particularly attractive, given the crucial role of energy demand elasticities and the speed of adjustment of capital stock in response to various shocks in greenhouse gas mitigation cost studies. Firstly, the estimation of sectoral energy demand functions and of their components' demand, and hence inter-fuel substitution elasticities, recognises the dependence of energy demand not only on other variable factor inputs in the disequilibrium process but also on the quantities of quasi-fixed capital input. And, the fact that it is done in a dynamic optimisation context implies that the estimates of the short and long-run energy elasticities correspond to the Marshallian concept of the short and long-run elasticities. Secondly, the speed of adjustment of the capital stock to its long-run level after, for example, an energy price shock is endogenous and optimal at each point in time due, again, to the application of dynamic economic optimisation.

Very briefly, in this approach, a normalised restricted variable cost function – typically including labour, energy, materials and capital (as quasi-fixed capital) – is specified. The underlying production function incorporates the internal costs of adjustment associated with the fixed factor(s). The short-run demand functions for the variable factors are obtained by invoking the Shephard-Uzawa-McFadden lemma. A dynamic economic problem, incorporating the short-run optimal demand functions and gross additions to the fixed factor(s), is set up and the first-order conditions (FOC) are obtained. The demand functions for the fixed factor(s) are generated from the FOC as an approximate solution to a linear differential equation system. Typically, also in this research, the cost function is chosen to be quadratic, at it greatly facilitates the linking of short and long-run responses.

As far as the econometric implementation is concerned, the model involves a system of equations containing one equation each for the variable factors and a net accumulation function for the fixed factor(s). Thus, in the case where labour, energy, materials and capital (a quasi-fixed factor) are the factors of production, the estimating system will comprise four equations: three short-run demand functions and the net investment function. In order to obtain the inter-fuel substitution elasticities, the weak separability assumption among the factor aggregates is invoked and the (unit) energy cost function is approximated by a linearly homogenous translog specification. This helps obtain both short and long-run elasticities of the different energy sources.

A different dynamic approach is followed in specifying the energy demand by the residential sector. As it is very difficult to obtain time-series data on the stock of energy using appliances, the capital stock adjustment is considered only in an implicit fashion. More precisely, two approaches are employed in modelling the interrelated demands for the various fuels. In one of the approaches, the AI demand system – the most popular among the family of commodity demand systems – is parametrised as a vector error correction model (VECM). As mentioned above, the model nests within it the generalised stock adjustment model of Nadiri and Rosen (1969) and the autoregressive error model developed by Berndt and Savin (1975). In the other case, a single equation approach is adopted in which the dynamic OLS (DOLS) model developed by Stock and Watson (1993) is used to model the interrelated energy demands.

1.6 Thesis – an outline

For the purposes of modelling energy demand, the economy is divided into seven sectors: agriculture; mining; manufacturing; transport and storage; electricity, gas and water; commercial; and residential. Energy consumption in each sector, with the exception of agriculture, construction and the residential sector, is divided into the consumption of electricity, gas, oil and coal. The residential energy consumption is divided into three categories – electricity, gas and a residual category. Expenditure on the residual category, which consists primarily of wood and fuel oil, is relatively small - only 8 per cent of total residential energy expenditure in 1998. For agriculture, only two fuels, electricity and oil, are considered, as the consumption of the other two fuels is very small. And, finally, for the construction industry, coal consumption is dropped because of its negligible use.

In Australia, energy consumption has undergone major restructuring since the 1970s as a result of the interaction among economic forces like affluence, population, technical change, supply shocks (the oil price hikes of the 1970s, for instance) and resource endowments, especially that of primary fuels such as coal and natural gas. A closer look at these energy data is justified, as the main aim of this research is to explain the energy consumption dynamics and the inter-fuel substitutions. Therefore, Chapter 2 illustrates the trends, since 1974, in the national energy sector, and in particular the trends in the fuel mix in the main energy consuming sectors. As the econometric analysis in the subsequent chapters investigates the substitution possibilities between the various fuels used and does not deduct the fuel produced from total fuel consumption, this chapter focuses on 'gross energy consumption' trends, as opposed to net energy trends. The chapter also presents trends in national greenhouse gas emissions.

The third chapter is devoted to studying the structure of consumer energy demand in Australia. To this end, as mentioned above, the underlying consumer preferences are represented by the AI expenditure function. A dynamic structure, to account for the stickiness of the energy-using appliances, is added by formulating the AI demand system as a VECM, which nests within it the stock adjustment and the autoregressive error models. The dynamic specification is applied to the national-level quarterly data spanning the period from the third quarter 1969 to the second quarter 1998. To close the model, non-energy household consumption expenditure is considered as another variable in addition to electricity, gas and other fuels.

The above dynamic model is also applied to a quarterly data set covering the period from the third quarter 1984 to the second quarter 1998 on a panel of five states. However, in this case, the dynamic structure is not significant and, as a result, the static AI demand system is implemented. This chapter includes yet another application of the AI system. In this case, weak separability between energy and non-energy consumption is invoked and the demand for electricity, gas and other fuels is estimated by applying the autoregressive error model to the national-level annual data from 1970 to 1998. The more general formulation of the VECM is not considered here owing to the small sample size.

The application of the dynamic OLS (DOLS) to modelling the consumer energy demand in Chapter 4 is essentially an attempt to get a second opinion on the inter-fuel substitution relationships. The statistical evidence in the previous chapter tends to favour complementarity in the electricity and gas use which is difficult to justify, as the two fuels are considered to be good substitutes in the areas of cooking and space and water heating. The DOLS – a single equation approach and thus much less attractive from a theoretical point of view – is chosen as it allows much more flexibility in terms of specifying dynamics. Interestingly, this approach finds strong substitution possibilities between electricity and gas.

The second part of this chapter projects residential energy consumption and associated CO_2 emissions over the period 2000 to 2010 using the estimated energy demand structure in this chapter and in the previous one. Both energy demand and CO_2 emissions are projected first assuming that the independent variables – fuel prices, average consumer price level and household income – follow the trend path of the last 10 years. In an alternative scenario, residential energy demand and emissions are projected assuming that a carbon tax is imposed on fuel consumption depending on the content of CO_2 of individual fuels.

Chapter 5 has two main aims. First, it reports the results of modelling the consumer demand for various fuels along with that of non-fuel household consumption expenditure. Second, it analyses the deadweight loss (DWL) from implementing the carbon tax. The first question has already been addressed at length in Chapter 3, where three applications of the AI demand system are reported. In order to address the second question, it is crucial that the underlying expenditure function be concave, at least for the most recent quarter/year included in the sample. However, in the previous estimates, the Slutsky matrix (SM) frequently failed to satisfy the conditions of negative semidefiniteness. In this chapter, the static AI model is re-estimated after incorporating local curvature conditions. The welfare analysis assumes constant returns to scale and thus perfectly elastic supply conditions and a complete tax pass-through. In addition, the carbon tax revenue is assumed to be recycled in the form of a payroll tax deduction, leaving the general and non-fuel price levels unchanged.

Chapter 6 models the inter-fuel substitution structure of the Australian commercial and industrial sectors by dividing the two sectors into 37 industries and categorising energy employed into electricity, gas, oil and coal. Owing to the non-availability of adequate data on the level of output, capital stock and some other factor inputs, the production structure of an industry is assumed to be weakly separable in capital, labour, materials and energy aggregates, which, in turn, are assumed to be homothetic – linearly homogenous – in their components. The resulting unit energy cost function to the optimising agent is represented by a translog specification. In addition to the relative fuel prices, a trend variable is included in the set of regressors with a view to capturing the fuel efficiency biases, if any, of changing technology. The inter-fuel substitution structure for each of the 37 industries is estimated using national-level annual data from 1974 to 1998.

In the above analysis total energy demand by industry is taken as an exogenous variable, as at the level of industrial detail sought in the analysis, data on other factor aggregates – capital, labour, and non-energy materials – and output could not be obtained. In order to investigate the price responsiveness of the aggregate energy demand and the nature of the relationship between energy and other factor aggregates, including capital, it is crucial to endogenise total energy demand along with that of the other inputs. This issue is tackled in Chapter 7 by compromising at the level of industrial detail.

In this chapter, using a dynamic model of factor demands and invoking homothetic separability, the demand for aggregate factor inputs and energy components is modelled separately for the Australian economy with a view to analysing the energy substitution possibilities. The aggregate choice model, summarised by a quadratic cost function, is specified in terms of energy, materials, labour and quasi-fixed capital. The fuel choice model, represented by a homothetic translog cost function, includes electricity, gas, oil and coal. To this end, the economy is divided into seven sectors: agriculture; mining; manufacturing; electricity, gas and water; construction; transport; and services; and the resulting demand systems are estimated using national-level annual data spanning the period from 1974 to 1998.

The estimated energy demand structure, especially in Chapters 6 and 7, could only be overviewed due to the enormous number of parameters involved. However, in order to identify the energy conservation potential in various industries/sectors, a closer examination of these structures is required. Chapter 8 analyses such opportunities, first at an aggregate level such as manufacturing and electricity, gas and water – the picture painted in Chapter 7. Then, in order to further pinpoint the location of such potentials and, more importantly, to see whether the aggregate picture is not a distorted one because of aggregation across highly different industries – for instance, manufacturing – the corresponding sub-sector level inter-fuel elasticities are brought into the discussion.

The analysis focuses on major energy consuming sectors including manufacturing, electricity, gas and water, and transport, storage and communication. The residential and mining sectors with shares of 6.8 per cent and 5 per cent respectively in gross national energy consumption in 1998 are also included. Within manufacturing, fuel substitution opportunities are explored in six major energy consuming industries namely iron and steel, basic non-ferrous metals, petroleum refining, basic chemicals, wood, paper and printing, and cement, lime, plaster and concrete. These six industries accounted for approximately 80 per cent of the sector's gross energy consumption between 1974 and 1995. In electricity, gas and water, the public and private electricity generation sub-sectors are further investigated.

Chapter 9, the last chapter, summarises the thesis, along with a brief discussion of limitations of the research undertaken in this study and highlights areas for future research.

Notes

1 Fugitive-fuel emissions refer to those emissions not related to combustion for energy. These are generated from production, transmission, storage and distribution of fuels and from mining. In the case of oil and natural gas systems, for instance, it could take the form of venting, flaring, evaporation and leakage.

2 The tax is imposed in 1995 at the rate of $1.25 per tonne of CO_2. It reaches $13.8 per tonne of CO_2 in 2005 and is maintained at this level from 2005 onwards.

3 For a closely related study on 'no regrets' opportunities in the Australian energy sector, see Walker (1996).

4 For a survey of the international literature on the subject, readers are referred to Houthaker (1951), Balestra and Nerlove (1966), Taylor (1975, 1979), Fuss (1977), Atkinson (1978), Berndt *et al.* (1980), Hartman (1982, 1983), Pindyck (1979, 1980), Pindyck and Rotemberg (1983), McFadden and Fuss (1984), Al-Sahlawi (1989), Watkins and Berndt (1992), Atkinson and Manning (1995), Griffin (1996), Madlener (1996), and Considine (2000) among others. For a classic debate on the energy-capital complementarity issue, see Berndt and Wood (1975), Griffin and Gregory (1976), Pindyck (1979), Berndt and Wood (1979) and Griffin (1981) among others. For a recent discussion on this issue, see Raj and Veall (1996) and Atkeson and Kehoe (1999).

5 The two equations do not form a system of equations and more importantly are based on an *ad hoc* approach, as optimisition procedures are not considered explicitly.

6 This approach essentially follows the one suggested by Balestra and Nerlove (1966) where they explicitly recognise that energy demand is mostly captive in the sense that it is tied to the existing stock of energy-using capital.

7 The ratio of the short and the long-run elasticities is the same for all variables.

8 Alternatively, a short-run profit function can be specified.

9 See Berndt and Savin (1975) for an application of this model.

10 Extension to the case of more than one quasi-fixed factor is straight forward, see, for instance, Morrison and Berndt (1981) and Rezitis *et al.* (1999).

11 The quadratic specification has certain advantages over most other specifications. First, the Hessian matrix of second-order partial derivatives is a matrix of constants, which facilitates greatly the linking of short and long-run responses. Second, the estimated (optimal) investment equation is globally and locally valid, as the underlying differential equation approximating investment is linear due to the quadratic cost function specification (Denny *et al.* 1981:236).

2

Trends in energy consumption and greenhouse gas emissions

Synopsis

Gross energy consumption increased from 3.1 exa joules to 5.7 exa joules over the 25-year period to 1998, growing at an average annual rate of 2.6 per cent a year. While coal matched the pace of gross fuel consumption, the consumption of electricity and gas grew much faster and that of oil significantly slower, resulting in a major restructuring in the fuel mix. Despite the significant transformation in the energy sector, the combined share of the three major energy consuming industries – manufacturing, electricity, gas and water and transport – in gross energy consumption remained nearly stable at more than 80 per cent. Between 1990 and 1997, greenhouse gas emissions increased by 11 per cent to 431.1 million tonnes; the additional emissions, 95 per cent CO_2, arose almost solely from energy combustion.

2.1 Introduction

In Australia, energy consumption has undergone major restructuring since the 1970s as a result of the interaction among economic forces such as affluence, population, technical change, supply shocks (the oil price hikes of the 1970s, for instance) and resource endowments, especially those of primary fuels such as coal and natural gas. A closer look at these energy data is justified, as the main aim of this research is to explain the energy consumption dynamics and the inter-fuel substitutions. This chapter illustrates the trends, since 1974, in the national energy sector, and in particular the trends in the fuel mix in the main energy consuming sectors. The chapter also presents trends in national greenhouse gas emissions.

The econometric analysis in the subsequent chapters investigates the substitution possibilities between the various fuels used and does not deduct the fuel produced from total fuel consumption. This chapter, therefore, focuses on 'gross energy consumption' trends as opposed to net energy trends.[1] As mentioned in the introductory chapter, gross energy demand is divided into four fuels: electricity, gas, oil and coal. Also, for most of the analysis in this chapter, the economy is divided into eight sectors: agriculture; mining; manufacturing; electricity, gas and water; construction; transport; and services.

The rest of the chapter is organised as follows. Section 2.2 depicts trends in gross national energy consumption by fuel and then by sector. The next section, Section 2.3, analyses the trends in the fuel mix by sector in the eight-sector framework. Section 2.4 looks at the fuel consumption structure at the broadest possible level of industrial detail in which the economy is divided into 38 branches, including the residential sector. The trends in greenhouse gas emissions are discussed in Section 2.5.

2.2 Gross energy consumption

Gross energy consumption in Australia increased from around three exa joules (EJ)[2] in 1974 to 5.6 EJ in 1998, growing at an average rate of 2.6 per cent per year (Table 2.1 and Appendix Table A2.1).[3] Nearly four-fifths of this additional energy, approximately 2.6 EJ, was consumed during the last 15 years, 1983 to 1998, whereas the other one-fifth was used during the decade from 1974. The two oil shocks of the 1970s and the consequent recession which led to a significant drop in economic growth, resulted in a slowdown in energy consumption during the late 1970s and the early 1980s. However, the strong economic performance and more or less stable (real) energy prices since 1984 led to an unabated increase in fuel consumption.[4] Australia's population during this period of two and half decades increased by approximately 40 per cent; per capita energy use increased by more than 40 per cent, as total energy consumption rose by approximately 83 per cent during the same period (Figure 2.1). GDP, in contrast, increased by a factor of more than two, leading to almost a 20 per cent decline in the energy intensity of output.

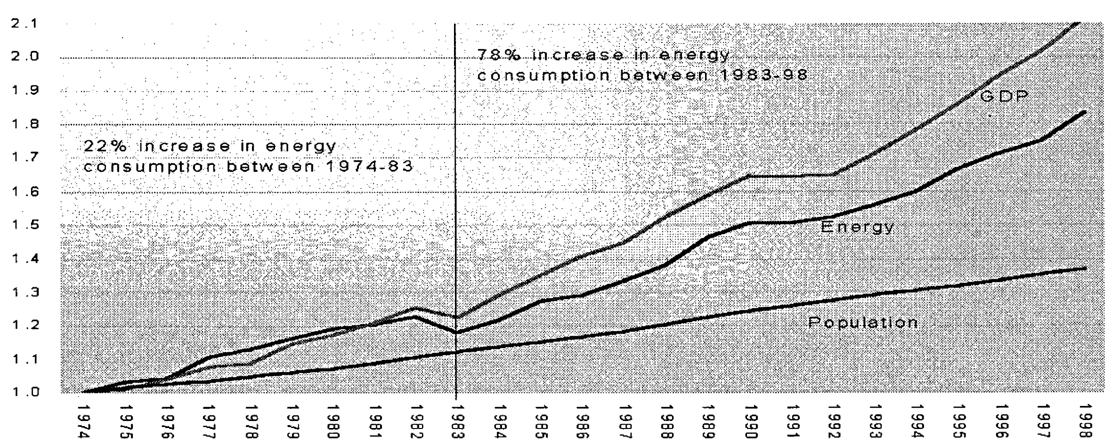
Table 2.1 **Gross energy consumption, by fuel**

Fuels	1974		1998		Growth
	Peta joules	Per cent	Peta joules	Per cent	rate*
Electricity	250.4	8.1	700.7	12.4	4.4
Gas	193.1	6.3	865.2	15.3	6.4
Oil	1299.3	42.1	1636.9	28.9	1.0
Coal	1342.9	43.5	2451.6	43.3	2.5
Total	3085.8	100.0	5658.1	100.0	2.6

Note: *- annual average (per cent) growth rate between 1974 and 1998.
Source: Bush *et al.* 1999. *Australian Energy: market developments and projections to 2014-15*, Research Report No. 99.4, Australian Bureau of Agricultural and Resource Economics, Canberra.

Coal, which experienced the largest absolute increase, about 1.1 EJ, over the 25-year period, accounted for more than two-fifths of the additional gross energy consumption during this period. Gas consumption, on the other hand, had the highest relative increase, growing at a rate of nearly 6.5 per cent per year. As a result, gas consumption more than quadrupled between 1974 and 1998 and its share increased by 9 percentage points from 6.3 per cent in 1974. The large natural gas discoveries and the development of gas transmission and distribution infrastructure led to this profound change in the energy sector.

Figure 2.1 **Energy consumption, GDP and population** (indices)

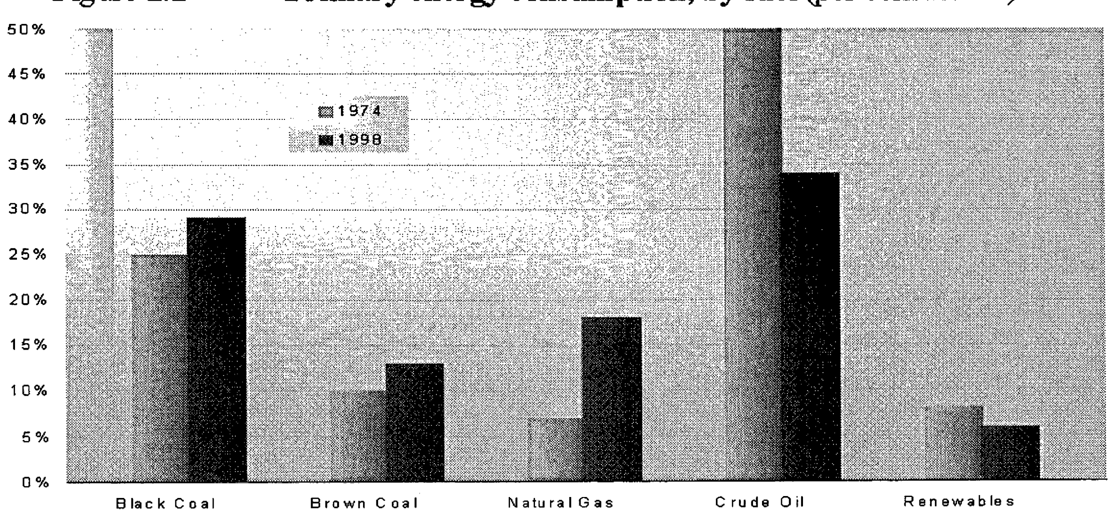


Sources: Australian Bureau of Statistics, 1999. *Australian System of National Accounts*, Catalogue No. 5204.0, Canberra. Bush *et al.* 1999. *Australian Energy: market developments and projections to 2014-15*, Research Report No. 99.4, Australian Bureau of Agricultural and Resource Economics, Canberra.

Growth in electricity use has also been very high; consumption grew at about 4.4 per cent a year over this period of 25 years, leading to a 2.8-fold increase and a 4.3 percentage point rise in the electricity share in gross energy consumption. As electricity in Australia is primarily generated from coal, growth in electricity demand helped maintain coal's share in gross energy consumption.[5] Oil, by contrast, experienced not only the smallest absolute increase, 338 peta joules (PJ), but also the lowest growth – it grew at less than 1 per cent a year over the entire period under consideration. The moderate growth in oil consumption is associated primarily with a rapid increase in (real) oil prices – real oil prices almost doubled during this period – and the availability of substitutes such as gas. The proportion of oil in gross energy consumption shrank from more than 40 per cent in 1974 to less than 30 per cent in 1998. The share of coal in gross energy consumption has been more or less stable at around 42-43 per cent.

However, the coal share in primary energy consumption increased by 7 percentage points to 42 per cent over the same period, due largely to its greater use in power generation – the share of black coal increased by 4 percentage points to 29 per cent and that of brown coal increased by 3 percentage points to 13 per cent (Figure 2.2). The share of crude oil in primary energy consumption fell even more sharply than in gross terms – from 50 per cent in 1974 to 34 per cent in 1998. Meanwhile, the share of natural gas in primary energy consumption more than doubled, from 7 per cent in 1974 to 18 per cent in 1998. The contribution of renewables such as wood, bagasse, hydroelectricity, and solar energy fell by 2 percentage points to 6 per cent in 1998.

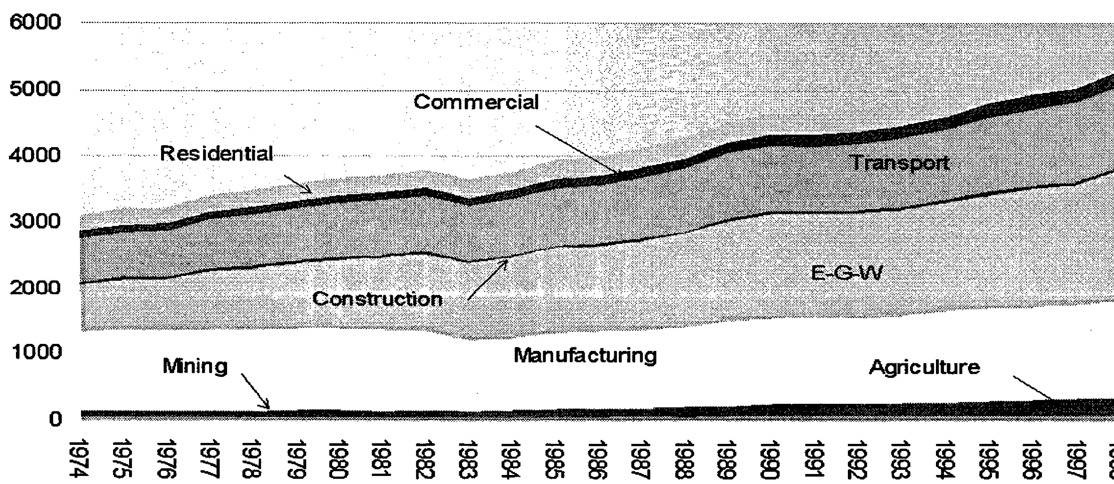
Figure 2.2 **Primary energy consumption, by fuel** (per cent shares)



Source: Bush *et al.* 1999. *Australian Energy: market developments and projections to 2014-15*, Research Report No. 99.4, Australian Bureau of Agricultural and Resource Economics, Canberra.

Three industries – manufacturing, E-G-W, and transport – are the dominant users of energy; the combined share of the three sectors stood at 85 per cent in 1974. The share has declined only slightly to a little less than 83 per cent in 1998 (Figure 2.3 and Appendix Tables A2.1 to A2.2). This slight contraction in share is not uniform across the three sectors. In fact, the share of the transport industry has been remarkably stable at around 22 per cent. In contrast, the manufacturing industry share fell by 13.1 percentage points to nearly 26 per cent in the last year from about 39 per cent in 1974. Energy consumption in the power sector grew at an average rate of 4.3 per cent – well above the average growth of 2.6 per cent – leading to an 11.5 percentage point inflation in its share in gross energy consumption. As a consequence of these opposite and roughly equally important trends, the combined shares of the three industries have been fairly stable.

Figure 2.3 **Gross energy consumption by sector** (peta joules)



Source: Bush *et al.* 1999. *Australian Energy: market developments and projections to 2014-15*, Research Report No. 99.4, Australian Bureau of Agricultural and Resource Economics, Canberra.

The agriculture, mining, construction and service industries are very small energy users. The share of the agricultural industry, for example, has been stagnant at around 1.3 per cent over the 25-year period. Similarly, the construction industry share has varied in the narrow range of 0.8-1 per cent. The mining industry, over this period of 25 years, experienced strong growth in output which led to a more than three-fold increase in energy consumption and the doubling of its share in gross energy consumption to nearly 5 per cent in 1998. The service industry's consumption grew at approximately 4 per cent a year, leading to an increase in its share from 2.6 per cent in 1974 to 3.6 per cent in 1998. The combined share of the four industries increased to 10.5 per cent in the last year from 7.5 per cent in 1974.

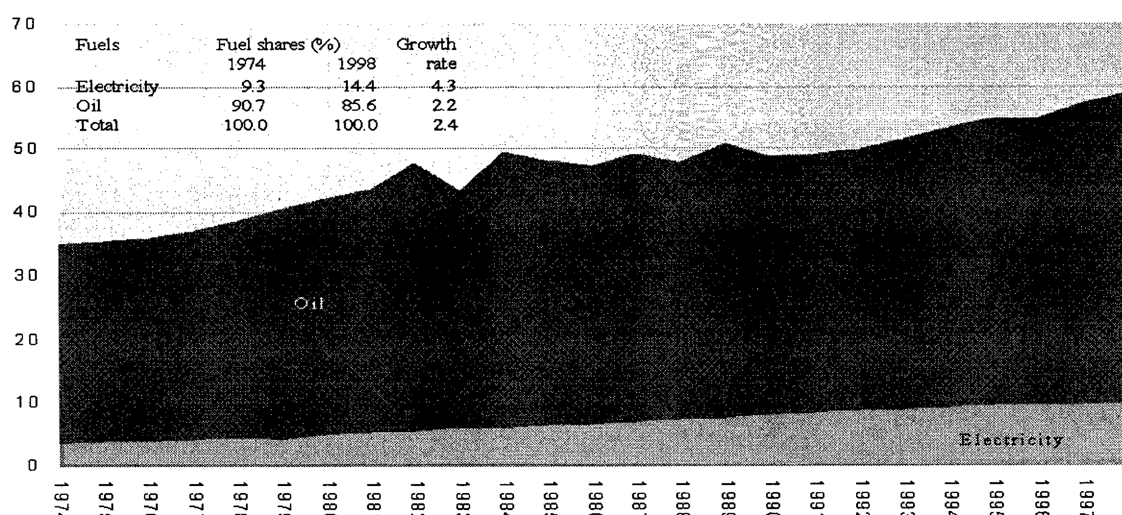
The residential sector's energy share was exactly equal to the combined share of the above four industries in 1974. However, it fell slightly to a little less than 7 per cent in 1998 as the sector experienced growth in energy use less than that of total energy consumption.

2.3 Energy consumption by sector and fuel

2.3.1 Agriculture

The agriculture sector has relied on electricity and petroleum products for its energy requirements and the consumption of the two other fuels has virtually been non-existent (Figure 2.4 and Appendix Table A2.3). Gross energy consumption by the industry over the 25-year period to 1998 rose from about 38.6 PJ to 68.8 PJ, growing at an average annual rate of 2.4 per cent – slightly less than the corresponding growth rate of 2.6 per cent in total energy consumption. Almost 79 per cent of the additional energy used by the sector during the period under consideration – 30.2 PJ – came from petroleum products and the remaining 21 per cent was contributed by electricity.

Figure 2.4 **Agriculture, energy consumption by fuel** (peta joules)



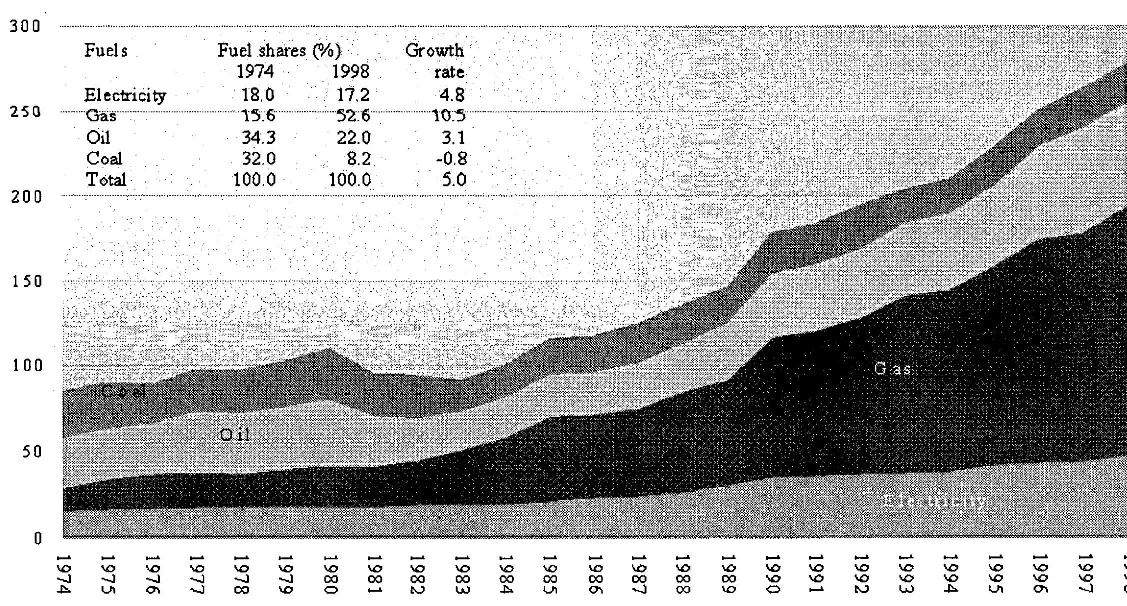
Source: Bush *et al.* 1999. ***Australian Energy: market developments and projections to 2014-15***, **Research Report No. 99.4, Australian Bureau of Agricultural and Resource Economics, Canberra.**

Electricity use in the sector, however, grew at a much faster pace of 4.3 per cent a year. Oil consumption, on the other hand, experienced moderate growth of 2.2 per cent, probably under the pressure of escalating oil prices during the late 1970s and the early 1980s. Technical change that took place during the last 25 years is likely to have augmented electricity consumption and diminished oil use in agriculture. As a result of greatly different energy growth rates, the electricity share in the sector's total energy consumption rose by a factor of 1.5 and that of oil shrank by about 5 percentage points to 85.6 per cent in the last year.

2.3.2 Mining

In contrast, the energy portfolio of the mining industry has been fairly diverse, although its dependence on coal has diminished remarkably from over 30 per cent to less than 10 per cent in the 25-year period to 1998 (Figure 2.5 and Appendix Table A2.4). Indeed, coal consumption by the sector declined at 0.8 per cent a year, leading to a 17 per cent reduction in use of the fuel in the industry. However, the mining sector as a whole experienced the highest growth in energy consumption, 5 per cent per annum, across all industries, largely attributable to growth in gas consumption. The sector had an 11-fold increase in gas consumption, making it the single largest fuel source in 1998 from a relatively minor component in the early 1970s. Electricity and oil could not maintain their shares despite growing at 4.8 per cent and 3.1 per cent respectively, due to very high growth in gas use by the sector.

Figure 2.5 **Mining, energy consumption by fuel** (peta joules)

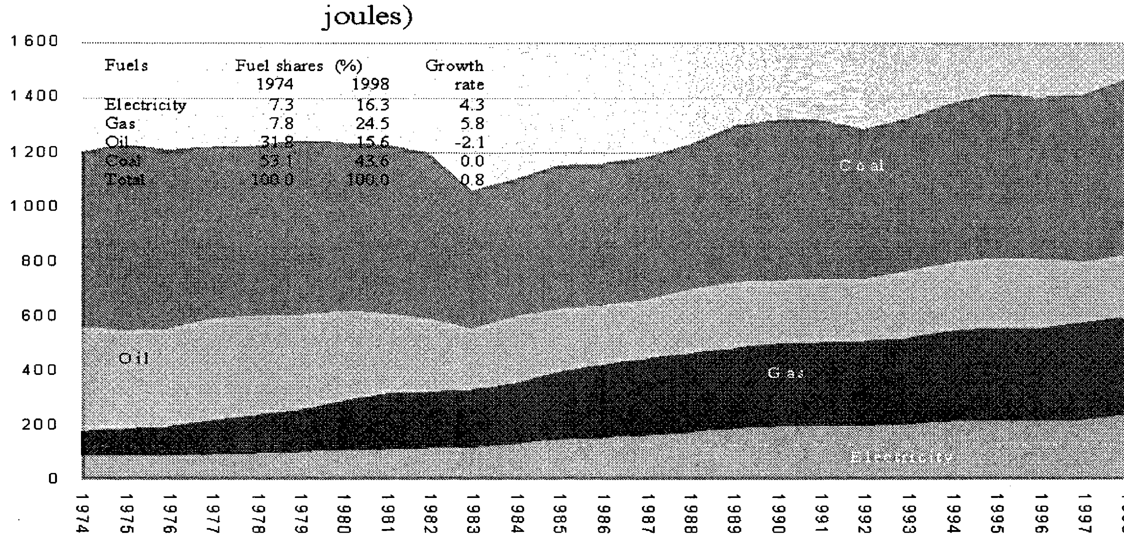


Source: Bush *et al.* 1999. *Australian Energy: market developments and projections to 2014-15*, Research Report No. 99.4, Australian Bureau of Agricultural and Resource Economics, Canberra.

2.3.3 Manufacturing

Energy use in manufacturing, the largest energy consuming sector until 1983 and the second largest since 1984, increased from 1.2 EJ in 1974 to 1.5 EJ in 1998, growing at the modest rate of 0.8 per cent a year (Figure 2.6 and Appendix Table A2.5). This is largely because of a 40 per cent reduction in oil demand, the second largest fuel source in the 1970s, and near stagnant coal consumption – the largest fuel source over the entire 25-year period. Electricity and gas use by the industry, on the other hand, grew rapidly over the period; electricity demand grew at 4.3 per cent and that of gas at 5.8 per cent a year.

Figure 2.6 **Manufacturing, energy consumption by fuel** (peta joules)



Source: Bush *et al.* 1999. *Australian Energy: market developments and projections to 2014-15*, Research Report No. 99.4, Australian Bureau of Agricultural and Resource Economics, Canberra.

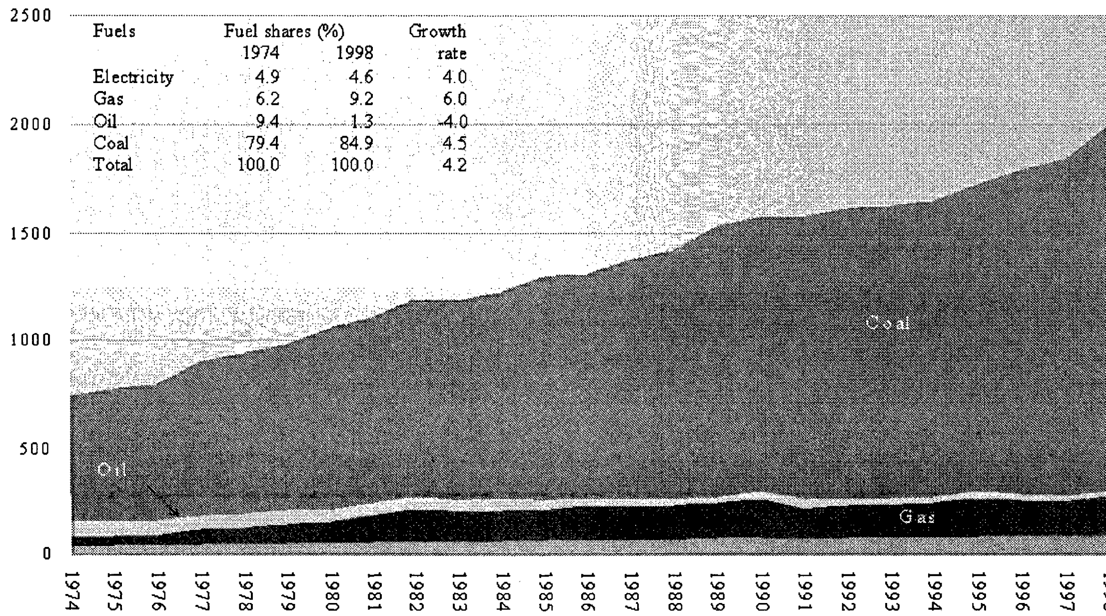
As a result, the sector's fuel structure changed dramatically over the past 25 years to 1998. The oil share in 1998, for instance, had fallen by one-half from its pre-oil crisis level. There was a relatively less dramatic reduction in the industry's dependence on coal, as its share declined from 53.1 per cent to 43.6 per cent over the 25-year period. The combined share of electricity and gas by contrast, increased to more than 40 per cent in 1998 from approximately 15 per cent in 1974, owing partly to a 2.7-fold increase in electricity and 3.8-fold jump in gas consumption in the industry. The rapid increase in the gas share in this sector is in large part because of the substitution of natural gas for oil in stationary appliances such as boilers and kilns. Similarly, the increased electricity share in the fuel mix is attributable to impressive growth in the aluminum industry (Bush *et al.* 1999:32).

2.3.4 Electricity, gas and water

The electricity, gas and water (E-G-W) sector, dominated by the electricity generation sector, has been the largest energy-consuming sector since 1983. Its share in gross energy consumption grew from about one-quarter in 1974 to more than 35 per cent in

1998, on the back of an impressive expansion of the power industry. Historically, E-G-W has depended heavily on coal for most of its energy requirements, as the coal share was about 80 per cent of gross energy consumed by the sector during the early 1970s (Figure 2.7 and Appendix Table A2.6). The sector's reliance on coal increased, particularly during the late 1990s; in 1998 the coal share was estimated at about 85 per cent. Because of the above-average growth in coal use and its overwhelming dominance in the fuel mix of the sector, more than 88 per cent of the additional energy of 1.1 EJ used in the industry during the period under consideration consisted of coal.

Figure 2.7 **E-G-W, energy consumption by fuel** (peta joules)



Source: Bush *et al.* 1999. ***Australian Energy: market developments and projections to 2014-15***, Research Report No. 99.4, Australian Bureau of Agricultural and Resource Economics, Canberra.

Growth in gas use in the industry, like most other industries, has been very high; it rose from around 46 PJ in 1974 to nearly 184 PJ, growing at an average rate of approximately 6 per cent a year. As a result, the gas share in the fuel mix increased by 3 percentage points to 9.2 per cent. However, in recent years gas use in the industry has been more or less stagnant, mainly due to the electricity market reform process that began with the disaggregation and corporatisation of state electricity utilities in Victoria in 1993. The competitive pressure on power producers operating in the southeast-interconnected electricity market rose sharply when the wholesale electricity prices fell dramatically in 1996 due to the start of a wholesale electricity market in New South Wales (NSW) in May 1996.[6] As a result, the capacity utilisation of the coal-fired power plants – particularly the brown coal-fired power plants – in the interconnected region rose significantly and that of gas-fired plants fell noticeably. This was primarily because the brown coal power generators are very low cost producers of electricity and significant increases in capacity use were possible at low cost (Bush *et al.* 1999:36).[7]

Oil consumption in the sector during this period shrank at an average rate of 4 per cent a year, reflecting the adjustment process that began in the early 1970s as a result of the oil price hikes. Oil consumption in the industry fell to 25.8 PJ by 1998 – less than two-fifths of its 1974 level. As a consequence of this dramatic contraction, the oil share fell from approximately 10 per cent to just 1.3 per cent in the 25-year period to 1998. Electricity has not been a prominent fuel source in the E-G-W sector, accounting for around 5 per cent of the gross energy consumed by the industry in 1974. Nonetheless, electricity use has maintained its importance in the fuel mix of the industry.

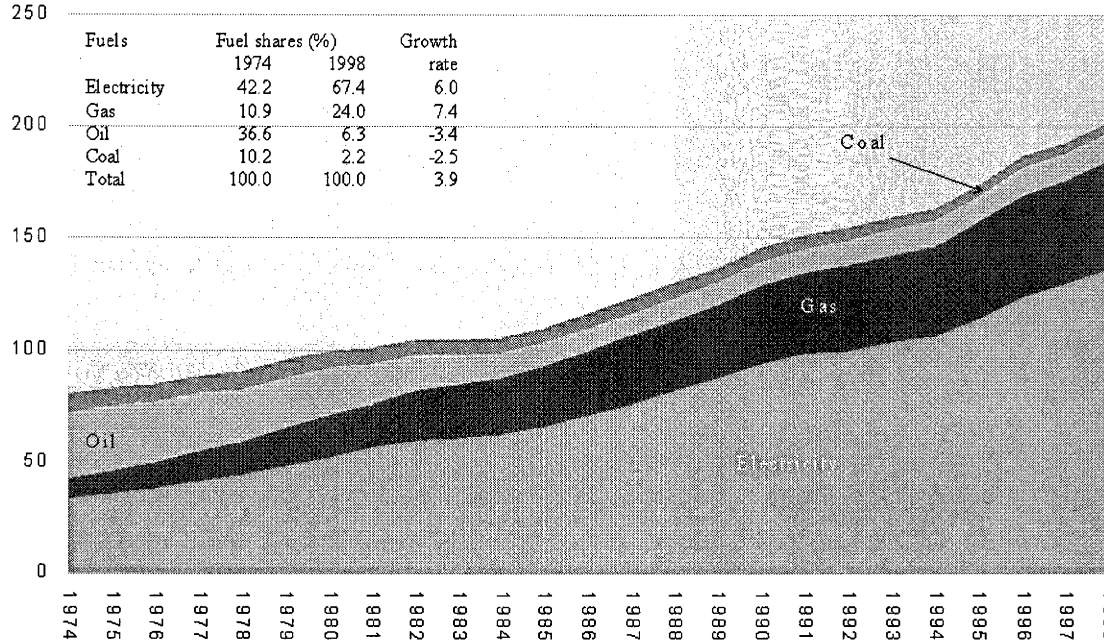
2.3.5 Construction and transport

The construction and transport industries have two common features as far as the structure of energy consumption is concerned, although the former is the smallest industry in terms of energy consumption and the latter is the third largest sector. Firstly, the two sectors have been able to maintain their share of the energy market – the construction industry at around 0.8 per cent and transport at 22 per cent. Secondly, energy is almost exclusively sourced from petroleum products. In the construction industry, for instance, the oil share has been above 99 per cent throughout the period, and, in the transport industry, the oil share has varied between 99.5 and 98.1 per cent (Appendix Tables A2.7 to A2.8). Coal consumption is virtually nil in the two sectors.

2.3.6 Commercial

The commercial sector, a relatively small energy consuming sector, experienced 4 per cent growth a year in energy consumption during the 25-year period under consideration, leading to a 2.5-fold increase in the sector's total energy use to 201.8 PJ in 1998 (Figure 2.8 and Appendix Table A2.9). During the early 1970s, electricity and oil were the main energy sources, with a combined share of 80 per cent in 1974. However, oil consumption fell by 60 per cent to 12.8 PJ in 1998. In contrast, electricity consumption in the industry quadrupled to 136 PJ, owing to an average growth rate of 6 per cent a year. In the same period there was a 5.5-fold increase in gas consumption from a mere 8.7 PJ to 48.5 PJ. Coal, which accounted for more than 10 per cent of the sector's energy demand in 1974, shrank by 40 per cent to just 4.5 PJ in 1998.

Figure 2.8 **Services, energy consumption by fuel** (peta joules)



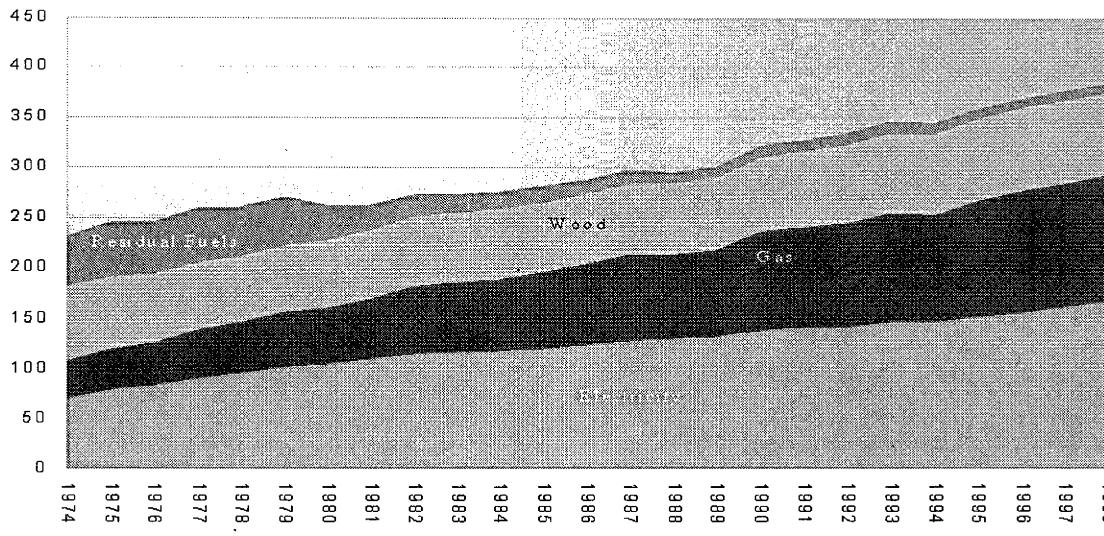
Source: Bush *et al.* 1999. *Australian Energy: market developments and projections to 2014-15*, Research Report No. 99.4, Australian Bureau of Agricultural and Resource Economics, Canberra.

As a result of this massive restructuring in the fuel mix of the industry, the oil share fell to just 6.3 per cent in 1998 from over 36 per cent in 1974. Coal's share fell by 80 per cent to 2.2 per cent in 1998 from over 10 per cent in 1974. The electricity and gas shares, on the other hand, increased by factors of 1.6 and 2.2 respectively, making the two fuels the main energy source for the commercial sector – the combined share of the two fuels was more than 91 per cent in the last year of the period.

2.3.7 Residential

The structure of consumer energy demand in the Australian residential sector has changed significantly during the past two and a half decades as is depicted in Figures 2.9 to 2.12 and Appendix Table A2.10. The share of wood and other residual fuels in overall energy use, for instance, has gone down from more than one half in the early 1970s to a little less than one quarter in 1998.[8] This has happened despite the fact that wood consumption has been remarkably resilient despite changing energy use over time. Consumption of this traditional energy source has, in fact, increased from 75 PJ in 1974 to 82 PJ in 1998, growing at an average annual pace of nearly half a percentage point.

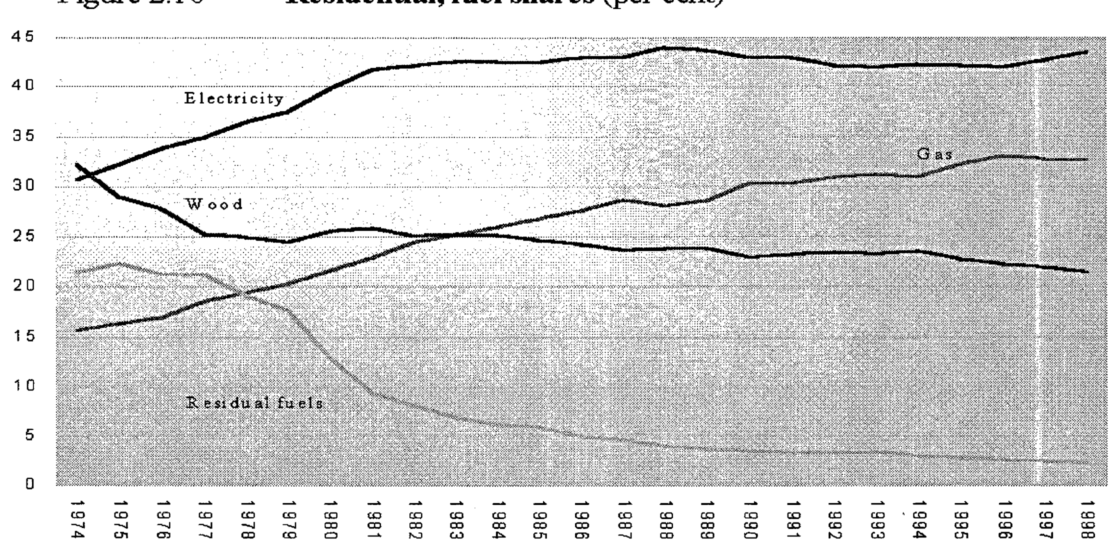
Figure 2.9 **Residential, energy consumption by fuel** (peta joules)



Source: Bush *et al.* 1999. *Australian Energy: market developments and projections to 2014-15*, Research Report No. 99.4, Australian Bureau of Agricultural and Resource Economics, Canberra.

The use of electricity and gas for domestic cooking, cooling, heating and lighting has increased very rapidly over the period, due mainly to their declining (real) prices. Electricity consumption, for instance, grew at the rate of 3.6 per cent which resulted in a more than two-fold increase in its use by households. Gas use, in contrast, increased by a factor of five owing to an average annual growth rate of more than 5 per cent and, as a consequence, the gas/electricity ratio increased from roughly one-half to three-quarters by the end of 1998. Impressive growth of gas consumption is also attributable to the expansion of gas reticulation and transmission systems which began in the late 1960s.[9]

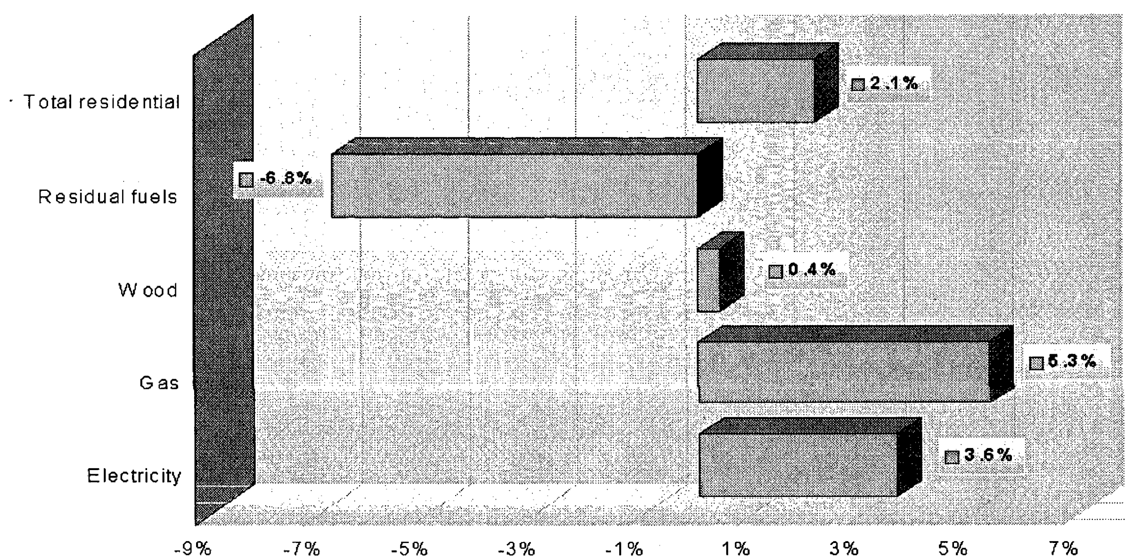
Figure 2.10 **Residential, fuel shares** (per cent)



Source: Bush *et al.* 1999. *Australian Energy: market developments and projections to 2014-15*, Research Report No. 99.4, Australian Bureau of Agricultural and Resource Economics, Canberra.

Consumption of the residual fuels declined from more than 60 PJ in 1974 to less than 20 PJ in 1998, an average annual rate of decline of almost 7 per cent. As a consequence, the consumption of residual fuels has fallen to almost negligible proportions from more than one quarter of total energy consumption in the early 1970s. This reduction in the use of residual fuels is attributable to the developments in energy consumption technology which have taken place during the past 30 years. More importantly, the real price of these fuels increased by almost 100 per cent during the past three decades while that of the two competing fuels declined considerably during the same period. These unfavourable price movements should explain most of the reduction in the use of residual fuels.

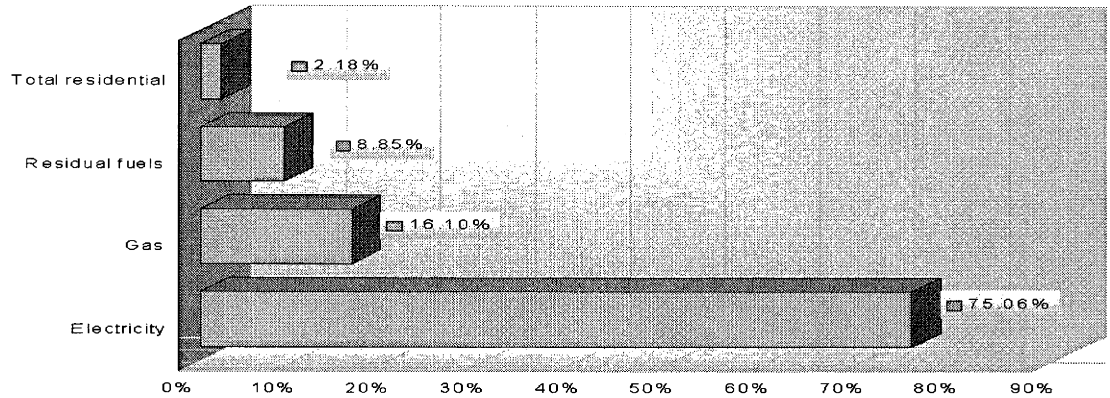
Figure 2.11 **Residential, energy growth rates by fuel** (per cent)



Source: Bush *et al.* 1999. *Australian Energy: market developments and projections to 2014-15*, Research Report No. 99.4, Australian Bureau of Agricultural and Resource Economics, Canberra.

Figure 2.12 graphs the average (per cent) shares of different fuels in total residential energy expenditure using current dollar data for the period 1970 through to 1998. Also in this figure is the total energy bill as a percentage of household spending. Wood is not treated separately because expenditure data, either nominal or real, on wood use is not available and, therefore, is a part of the miscellaneous category. Clearly, expenditure is dominated by electricity as approximately three-quarters of total energy expenditure is used to pay electricity bills. A little more than 16 per cent is spent on gas and the remaining fraction, approximately 9 per cent, is spent on all other types of energy including wood. As is obvious from Figure 2.12, energy expenditure constitutes only a minor part of private final consumption spending, roughly 2.2 per cent.

Figure 2.12 **Residential, expenditure shares by fuel** (per cent)



Source: Australian Bureau of Statistics, 1999. *Australian System of National Accounts*, Catalogue No. 5204.0, Canberra.

2.4 Energy structure in the 38 sub-sectors

Table 2.2 divides the Australian economy, including the residential sector, into 38 sectors and reports average energy consumption – between 1974 and 1995 – by the corresponding fuel shares.[10] The last column of the table shows gross energy consumption by industry/sub-sector in a typical year, whereas the second last column presents the relative fuel consumption by industry/sub-sector. Interesting patterns emerge from this presentation. Energy consumption across industries is highly variable, which can be seen more clearly from the second last column that presents the average energy use across industries as a proportion of total energy use.

Within the manufacturing industry, which accounted for more than 30 per cent of gross energy consumption between 1974 and 1995, the food, beverages and tobacco industry is a minor energy user. The industry, in a typical year, employed around 131 PJ which constituted 3.2 per cent of total energy consumption. The average fuel share in different industry sub-sectors varied between 0.0 to 0.3 per cent, with the exception of other food manufacturing which employed nearly two-thirds of gross energy consumed by the food, beverages and tobacco industry.

The other food manufacturing sub-sector sourced almost 89 per cent of its energy needs from wood, which is part of the coal category. In the other sub-sectors, the fuel mix is fairly diverse. In meat and meat products, for instance, all four fuel shares ranged between 20-30 per cent. In bakery products, however, coal use is relatively minor – the fuel share is less than 0.5 per cent. Bakery products, beverage and malt products, and tobacco industries depend significantly on gas, with a share greater than 40 per cent in each case.

Table 2.2 **Average energy consumption by fuel type and by industry/sector, 1974-95**

Sectors/Industries	Fuel shares				Average per year	
	Electricity	Gas	Oil	Coal	Per cent	Level (PJ)
Agriculture, forestry and fishing	12.3	0.0	87.7	0.0	1.3	51.9
Mining	18.8	38.2	25.0	18.0	3.3	131.8
Manufacturing					30.7	1236.5
Food, beverages and tobacco					3.2	130.8
Meat and meat products	25.0	23.6	29.9	21.5	0.3	12.8
Dairy products	14.6	24.6	25.0	35.8	0.3	11.2
Fruit and vegetable processing	19.6	24.5	30.0	25.9	0.1	4.3
Oil and fat	20.6	37.0	15.9	26.5	0.1	3.0
Flour and cereal products	31.9	35.5	11.2	21.4	0.1	3.4
Bakery products	21.5	46.3	31.7	0.5	0.1	4.3
Other food manufacturing	3.6	4.7	2.8	88.8	2.1	84.4
Beverage and malt products	21.8	47.1	18.0	13.1	0.2	6.8
Tobacco products	26.0	53.3	3.0	17.7	0.0	0.7
Textile, clothing, footwear and leather	37.6	37.2	12.7	12.5	0.4	15.0
Wood, paper and printing	23.0	26.0	10.5	40.5	1.6	63.1
Petroleum, coal and chemicals					6.4	257.6
Petroleum refining	3.5	7.9	88.6	0.0	2.6	105.2
Petroleum and coal products nec	1.8	6.4	8.5	83.3	0.3	10.8
Basic chemicals	6.2	33.0	57.3	3.5	3.3	132.5
Other chemicals, rubber and plastic	30.3	39.3	18.4	12.1	0.2	9.1
Non-metallic mineral products					2.3	92.0
Glass and glass products	9.3	74.2	16.0	0.4	0.3	12.6
Ceramics	7.4	65.2	18.2	9.2	0.7	29.5
Cement, lime, plaster and concrete	9.2	39.8	6.9	44.1	1.0	42.1
Non-metallic mineral products nec	16.5	36.4	15.2	31.9	0.2	7.9
Metal products					16.4	660.3
Iron and steel	3.8	4.0	2.7	89.5	10.6	427.8
Basic non-ferrous metals	27.6	25.5	26.3	20.6	5.5	223.1
Other metal products	38.1	47.1	12.3	2.4	0.2	9.3
Machinery and equipment	47.2	39.1	10.9	2.8	0.4	17.7
Electricity, gas and water					31.6	1272.6
Public electricity generation	5.1	8.2	1.8	84.9	28.9	1164.0
Private electricity generation	1.3	20.1	34.0	44.6	1.5	60.8
Gas production and distribution	0.3	77.3	20.4	2.0	0.6	23.9
Water, sewerage and drainage	0.3	77.3	20.4	2.0	0.6	23.9
Construction	0.3	0.4	99.3	0.0	0.9	36.5
Transport and storage	0.5	0.4	98.8	0.2	22.2	894.4
Commercial and services					2.9	118.1
Wholesale and retail trade	57.0	25.2	17.1	0.7	1.1	45.2
Communication	83.3	5.6	11.2	0.0	0.1	2.7
Finance, insurance, property & business	95.5	4.4	0.0	0.0	0.3	11.5
Government administration and defense	61.0	12.7	22.2	4.1	0.4	14.8
Education, health & community services	39.6	28.2	14.8	17.3	0.8	31.3
Accommodation, cultural and personal	70.8	24.0	2.4	2.9	0.3	12.7
Residential	40.6	23.5	9.8	25.6	7.2	289.2
Total					100.0	4031.2

Note: nec = not elsewhere classified.
Sources: Bush *et al.* 1999. *Australian Energy: market developments and projections to 2014-15*, Research Report No. 99.4, Australian Bureau of Agricultural and Resource Economics, Canberra and author's calculations.

The metal products industry (dominated by iron and steel) is a heavy energy user – with a share of total energy more than 16 per cent. In an average year between 1974 and 1995, the iron and steel industry used more than 427 PJ which translates into a share of 10.6 per cent in gross national energy consumption during the 22-year period to 1995. Nearly 90 per cent of the energy requirements was met from coal in this energy-dependent industry. In the case of basic non-ferrous metals, another big energy user, the energy mix is diverse with fuel shares ranging from 20.6 per cent for coal to 27.6 per cent for electricity.

The metal products industry is followed by the petroleum, coal and chemicals sub-sector with an energy share of 6.4 per cent. Petroleum refining and basic metals dominate the sub-sector, with energy shares of 2.6 per cent and 3.3 per cent respectively. The two industries met most of their fuel requirement from petroleum products; the oil share for the petroleum refining industry was more than 88 per cent and that in the case of basic chemicals at 57.3 per cent.

Clearly, both total energy use and fuel mix are markedly different across the individual industries included in this sector. The iron and steel industry is the biggest user within the sector and relies heavily on coal. The non-metallic mineral product industry by contrast is a small user of energy and relies mostly on electricity and gas. Given this heterogeneity in fuel use and fuel mix across industries included in the sector, it is more appropriate to formulate the inter-fuel substitution problem at the level of individual industries rather than at the broad sectoral level.

The electricity, gas and water sector – the largest energy consuming sector over the 22-year period to 1995 – employed, in an average year, 1272.6 PJ of energy, comprising primarily brown and black coal. Coal is an especially important fuel source in public electricity generation and overwhelmingly dominates the electricity, gas and water sector, with an average consumption of 1164 PJ a year. The private sector power plants used relatively more gas – the fuel share of gas stands at 34 per cent – but the private sector has been a very small player in electricity generation. The other two sub-sectors included in this industry – gas production and distribution, and water, sewerage and drainage – are very minor energy users and mostly on gas and oil.

The commercial sector is also a small user of energy. All the industries included in this sector consume less than 3 per cent of the total energy used. Individual industries included in this sector rely mostly on electricity. As an extreme example, the finance, property and business sector fulfilled more than 95 per cent of its energy needs from electricity.

2.5 Greenhouse gas emissions

In Australia, greenhouse gas emissions increased by 40.7 million tonnes (Mt) of carbon dioxide equivalent (CO_2-e) between 1990 and 1997, an increase of 11 per cent (Table 2.3). A cursory look at the table reveals that growth in the emission of different gases has been markedly different. Emissions of CO_2 – the largest greenhouse gas – increased by 16.5 per cent, well above the increase of 11 per cent. Nitrous oxide (N_2O) with an increase of 15.6 per cent and methane (CH_4) with an increase of 1.8 per cent followed. The perfluorocarbons (PFC) – a relatively minor greenhouse gas but with a relatively high global warming potential (GWP)[11] – declined by nearly three-quarters over the 1990-97 period.[12]

Table 2.3 **Greenhouse gas emissions, 1990-97**

Gases	1990		1997		Change: 1990-97		Increase (per cent): 1990-97
	Mt of CO_2-e	Per cent	Mt of CO_2-e	Per cent	Mt of CO_2-e	Per cent of total change	
CO_2	246.8	63.5	287.5	66.7	40.7	95.3	16.5
CH_4	114.4	29.4	116.5	27.0	2.1	4.9	1.8
N_2O	22.5	5.8	26	6.0	3.5	8.2	15.6
PFCs	4.9	1.3	1.3	0.3	-3.6	-8.4	-73.5
Total	388.6	100.0	431.3	100.0	42.7	100.0	11.0

Note: Mt = million tonnes.
Source: NGGIC, 1999. *National Greenhouse Gas Inventory 1997 with Methodology Supplements*, National Greenhouse Gas Inventory Committee, Canberra.

As a consequence of the highly different emission growth rates, the share of CO_2 increased from 63.5 per cent in 1990 to two-thirds of national emissions in 1997. The CO_2-e share of CH_4 – the second biggest contributor – fell by 2.4 percentage points to 27 per cent in 1997 because of the below-average increase in the CH_4 emissions: 1.8 per cent. The slow growth in emissions is attributable to two factors. First, the transport sector CH_4 emissions declined owing to an increase in the number of light vehicles with three-way catalytic converters. Second, over this period prescribed burning and wildfire declined, leading to a fall in the CH_4 emissions from forestry (NGGIC 1999). More than 95 per cent of the additional GHG emissions between 1990-97 were accounted for by CO_2.

Probably more interesting from this study's viewpoint is to examine the emission trends by sector. The GHG emissions by sector are presented in Table 2.4 by dividing the economy into five sectors: energy, industrial processes, agriculture, forestry and other, and waste. The energy sector, in turn, is divided into the emissions from stationary sources, transport and fugitive emissions. Figure 2.13 plots the increase in emissions between 1990 and 1997 by sector.

Table 2.4 **Greenhouse gas emissions by sector, 1990-97**

Sectors	1990		1997		Change: 1990-97	
	Mt of CO_2-e	Per cent	Mt of CO_2-e	Per cent	Mt of CO_2-e	Per cent of total change
Energy	296.7	76.4	339	78.6	42.3	99.1
Stationary energy	205.8	53.0	237	55.0	31.2	73.1
Transport	61.5	15.8	72.5	16.8	11	25.8
Fugitive	29.4	7.6	29.5	6.8	0.1	0.2
Industrial processes	12.1	3.1	9.0	2.1	-3.1	-7.3
Agriculture	92.1	23.7	94.2	21.8	2.1	4.9
Forestry and other	-27.1	-7.0	-26.5	-6.1	0.6	1.4
Waste	14.8	3.8	15.6	3.6	0.8	1.9
Total emissions	388.6	100.0	431.3	100.0	42.7	100.0

Note: Mt = million tonnes.
Source: NGGIC, 1999. *National Greenhouse Gas Inventory 1997 with Methodology Supplements*, National Greenhouse Gas Inventory Committee, Canberra.

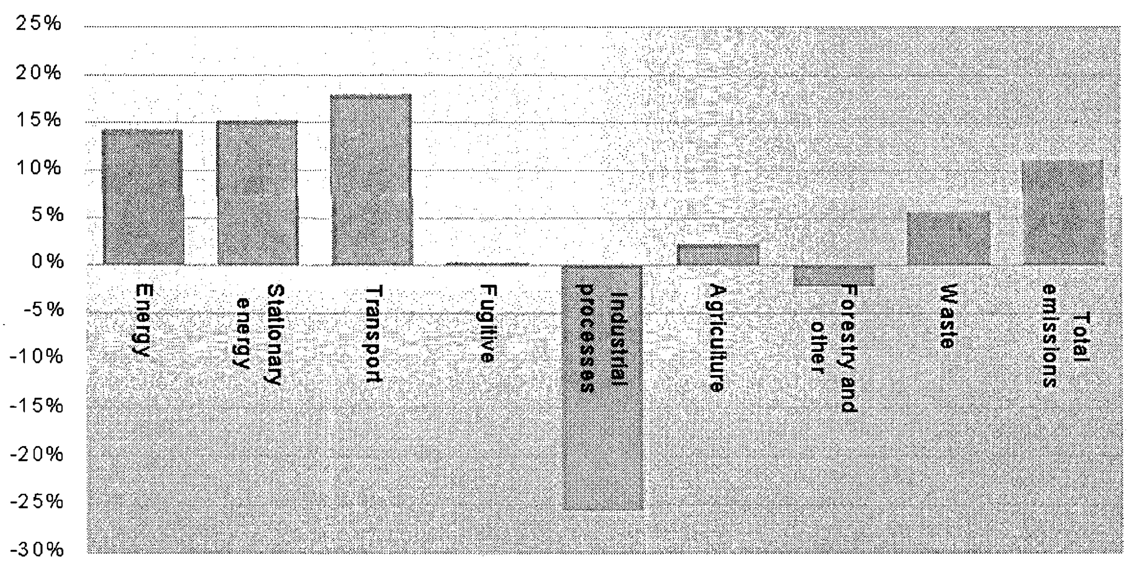
In 1990, the energy sector accounted for more than three-quarters of total emissions with 296.7 Mt of CO_2-e emissions. The energy sector, in turn, is dominated by the stationary energy sources such as electricity generation, which accounted for more than half of the 1990 emissions. Transport energy sources follow with 61.5 Mt CO_2-e, equivalent to 15.8 per cent, while fugitive emissions held a 7.6 per cent share in national emissions in 1990.

Agriculture – the largest source of CH_4 and N_2O and the second largest contributor to total emissions (after the energy sector) – accounted for nearly one-quarter of total emissions in 1990. The agriculture sector emissions are largely generated from the livestock sub-sector: CH_4, for instance, is emitted as a result of microbial fermentation associated with feed digestion. Similarly, the decomposition of animal waste causes some CH_4 and N_2O emissions. The crop sub-sector emissions result mostly from the application of fertilisers to agricultural soils and the burning of savannas to increase grass production.

In contrast to energy and agriculture, changes in forest and other woody biomass removed more than 27 Mt CO_2-e from the atmosphere, amounting to -7 per cent of national emissions for the year. Industrial processes and waste are relatively minor sectors in terms of emissions. In 1990, waste emissions, primarily CH_4 generated from anaerobic decomposition of organic matter in landfills and sewage facilities, were estimated at 14.8 Mt of CO_2-e, accounting for 3.8 per cent. Emissions from the industrial processes sector, which are a by-product of different production processes such as mineral and metal production, were equivalent to 12.1 Mt CO_2-e, slightly more than 3 per cent of total emissions for the year.

Between 1990 and 1997, total emissions increased by 42.7 Mt, or 11 per cent, primarily because of a 14.3 per cent growth in the energy sector emissions. As a result of the above-average growth in the energy sub-sector emissions, its share increased by 2.2 percentage points to 78.6 per cent. Within the energy sector, the share of stationary energy and transport increased by two and one percentage points, respectively, and that of the fugitive sector fell by 0.8 percentage points to 6.8 per cent. Because of the energy sector's overwhelming position in total emissions and its above-average growth during the eight-year period, the sector accounted for almost all of the additional emissions of 42.7 Mt between 1990 and 1997.

Figure 2.13 **Growth in greenhouse gas emissions by sector, 1990-97** (per cent change)



Source: NGGIC, 1999. *National Greenhouse Gas Inventory 1997 with Methodology Supplements*, National Greenhouse Gas Inventory Committee, Canberra.

The agriculture sector emissions increased at a relatively minor pace of 2.3 per cent to 94.2 Mt in 1997. The sector's relative standing, as a result of slower than average growth, weakened by nearly 2 percentage points to 21.8 per cent. Growth in waste emissions has also been mild, 5.4 per cent, resulting in a small contraction in its share in national emissions. In contrast, in 1997, emissions from industrial processes fell by more than one-quarter to 9 Mt in 1997 from over 12 Mt in 1990, leading to a one-percentage point deflation in its share to 2.1 per cent in 1997. Also, the forestry sector removed slightly less GHG from the atmosphere in 1997: the GHG removal dropped by 0.6 Mt to 26.5 Mt in 1997.

2.6 Summary

The chapter employed the national level annual data from 1974 to 1998 on energy consumption, and greenhouse gas emissions data from 1990 and 1997, to illuminate trends in national energy consumption, its mix and greenhouse gas emissions. The trends in energy consumption and greenhouse gas emissions are summarised below:

- Gross national energy consumption increased from 3.1 exa joules in 1974 to 5.7 exa joules in 1998, growing at an average rate of 2.6 per cent a year.
- Nearly four-fifths of this additional energy, approximately 2.6 exa joules, was consumed during the last 15 years, 1983 to 1998.
- While the coal share remained approximately stable at around 43 per cent, the oil share fell from 42.1 per cent to less than 29 per cent during this period.
- Electricity and gas consumption, on the other hand, grew much faster, leading to significant improvements in their relative standing in the fuel mix. The electricity share increased by a factor of 1.5 to 12.4 per cent while that of gas increased 2.4-fold to 15.3 per cent.
- Three industries – manufacturing, electricity, gas and water and transport – dominate the energy sector.
- While the transport sector's share in gross national energy consumption remained roughly stable at around 22 per cent, the share of the power sector increased by 11.5 percentage points to above 35 per cent and that of manufacturing declined by 13 percentage points to 26 per cent in 1998.
- The fuel mix in transport and power is overwhelmingly dominated by a single source: in transport more than 98 per cent energy is sourced from oil while coal accounts for about 88 per cent of gross energy consumption in the power sector.
- The energy mix in manufacturing is fairly diverse: coal is the main fuel source followed by gas, oil and electricity.
- Six manufacturing industries account for more than four-fifths of the manufacturing sector's total energy consumption. Indeed, two industries – iron and steel and basic non-ferrous metals – account for more than one-half of the sector's total energy consumption.

- More than one-half of the manufacturing sector's total coal consumption is used in one industry, iron and steel.
- The mining sector, with a share of 5 per cent in gross national energy consumption in 1998, experienced the fastest growth in energy consumption, 5 per cent a year.
- The commercial sector, a relatively small energy consuming sector, depends largely on electricity and gas.
- The residential sector accounts for less than 7 per cent of gross national energy consumption and depends mainly on electricity and gas.
- Between 1990 and 1997, national greenhouse gas emissions increased by 11 per cent to 431.3 million tonnes, largely CO_2.
- The energy sector emissions, both from combustion and non-combustion sources, accounted for nearly four-fifths of national emissions in 1997.

Notes

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[1] Gross energy consumption consists of the total quantity consumed of primary fuels – energy sources obtained directly from nature, for instance, coal, crude oil, hydro electricity, solar energy and wood – and derived fuels, such as briquettes, coke, petroleum products and thermal electricity. Net energy consumption, on the other hand, equals total quantity of primary and derived fuels consumed less the quantity of derived fuels produced. Final energy consumption equals net energy consumption defined above less energy consumed in conversion, transmission and distribution (Bush *et al.* 1999:xi). The terms 'gross energy consumption' and 'total energy consumption' will be used interchangeably unless otherwise specified.

[2] Exa joules (EJ) = 10^{18} joules, Peta joules (PJ) = 10^{15} joules.

[3] Over the same period, the net energy consumption increased to 4.8 EJ in 1998, growing at an average rate of 2.6 per cent.

[4] The recession of the early 1990s moderated growth in energy consumption for two to three years.

[5] The share of coal fuel in thermal electricity generation increased from 86.9 per cent in 1974 to 89.8 per cent in 1998. The share of natural gas in thermal electricity generation rose from 5.4 per cent to 9 per cent and that of oil fell from 7.7 per cent to 1.2 per cent over the same period.

[6] New South Wales, including the Australian Capital Territory (ACT), South Australia and Victoria constitute the southeast-interconnected electricity market.

[7] In the integrated region the capacity utilisation rate in the brown coal-fired power plants increased from two-thirds in 1996 to nearly 84 per cent in 1998. The corresponding rate for the black coal based plants improved by nearly 1 percentage point. Over the same period, the capacity utilisation rate in gas-fired power generators fell to 16 per cent from 28.4 per cent. As a consequence, the brown coal share in thermal electricity generation of the interconnected region's fossil fuel mix increased by 4.7 percentage points from 43.2 per cent in 1996 and that of gas fell by nearly 2 percentage points over the same period (Bush *et al.* 1999:34-5).

[8] Residual fuels include black coal, coke, brown coal briquettes, lighting kerosene, heating oil, solar energy, automotive diesel oil and industrial diesel fuel. The category is dominated by heating oil and lighting kerosene, especially during the 1970s. Gas consists of natural gas and town gas.

[9] The proportion of Australian homes connected to gas reticulation systems had increased to 43.3 per cent by 1997 (AGA 1998).

[10] The fuel consumption data from 1996 to 1998 are not available at the level of detail sought in this section.

[11] The GWP of a gas is an index which is defined as the cumulative radiative forcing between the present and some chosen time horizon, typically 100 years, caused by a unit mass of gas emitted now, expressed relative to that of some reference gas, typically CO_2. The GWP for gases included in this analysis are as follows: CO_2 =1, CH_4 = 21, N_2O = 310, and PFC = 6500.

[12] The PFC emissions, associated with aluminum production, continuously declined during this period due to improvements in production methods.

Appendix Table A2.1 **Gross energy consumption by industry, 1974-98** (peta joules)

Years	AGR	MNG	MNF	EGW	CNS	TRS	CMR	RSD	TOT
1974	38.6	85.4	1201.9	737.2	25.9	685.4	80.1	231.3	3085.8
1975	39.3	90.3	1229.3	774.5	29.0	701.0	83.0	246.3	3192.7
1976	40.0	89.8	1210.2	800.9	28.9	714.9	84.8	246.4	3215.9
1977	41.2	98.3	1222.1	906.1	35.8	761.9	88.4	260.2	3414.2
1978	43.3	98.0	1225.3	939.9	35.4	798.7	90.2	261.0	3491.7
1979	44.9	103.2	1245.1	979.2	37.7	812.9	95.2	270.5	3588.7
1980	47.1	110.3	1237.3	1056.4	38.3	824.6	99.5	261.9	3675.3
1981	48.8	96.6	1228.6	1106.2	37.6	835.2	101.2	262.8	3717.1
1982	53.5	94.5	1199.3	1190.4	39.0	843.8	104.7	272.8	3798.0
1983	49.7	92.6	1063.0	1185.6	34.9	837.0	104.5	273.2	3640.5
1984	55.7	101.0	1102.3	1221.9	33.3	864.1	105.7	276.0	3760.0
1985	54.7	116.2	1153.5	1296.8	31.2	892.1	109.9	282.1	3936.5
1986	54.0	118.0	1163.7	1307.7	34.7	906.3	116.2	288.4	3989.1
1987	56.4	124.8	1185.7	1374.3	34.9	922.1	123.0	298.1	4119.2
1988	55.4	136.4	1228.7	1416.6	39.4	966.0	129.5	296.2	4268.2
1989	58.4	146.9	1295.9	1531.2	41.6	1004.9	136.7	301.5	4517.2
1990	56.9	178.2	1320.3	1573.2	41.1	1012.5	145.6	322.3	4650.1
1991	57.7	183.3	1318.6	1574.4	37.2	1003.0	151.1	327.8	4653.1
1992	58.7	194.6	1288.0	1612.7	39.3	1024.3	154.4	334.6	4706.3
1993	60.6	203.3	1323.2	1623.9	41.7	1049.6	159.0	347.1	4808.4
1994	62.5	209.9	1382.3	1651.5	43.1	1080.2	162.5	344.5	4936.4
1995	64.4	228.7	1413.2	1727.6	44.3	1137.2	173.3	358.6	5147.4
1996	64.5	250.5	1400.7	1790.9	43.9	1181.6	186.9	369.4	5288.4
1997	67.0	263.4	1410.1	1840.5	45.6	1203.0	192.6	377.4	5399.6
1998	68.8	278.2	1465.3	2001.7	47.0	1210.7	201.8	384.6	5658.1
Ratio[a]	**1.8**	**3.3**	**1.2**	**2.7**	**1.8**	**1.8**	**2.5**	**1.7**	**1.8**
Growth rate[b]	**2.4%**	**5.0%**	**0.8%**	**4.2%**	**2.5%**	**2.4%**	**3.9%**	**2.1%**	**2.6%**

Notes: a- 1998 value divided by the corresponding 1974 value, b- period average growth rate. AGR = agriculture, MNG = mining, MNF = manufacturing, EGW = electricity, gas and water, CNS = construction, TRS = transport, CMR = commercial, and RSD = residential.
Source: Bush *et al.* 1999. *Australian Energy: market developments and projections to 2014-15*, Australian Bureau of Agricultural and Resource Economics, Canberra.

Appendix Table A2.2 **Gross energy consumption by industry, 1974-98** (per cent shares)

Years	AGR	MNG	MNF	EGW	CNS	TRS	CMR	RSD	TOT
1974	1.3	2.8	38.9	23.9	0.8	22.2	2.6	7.5	100.0
1975	1.2	2.8	38.5	24.3	0.9	22.0	2.6	7.7	100.0
1976	1.2	2.8	37.6	24.9	0.9	22.2	2.6	7.7	100.0
1977	1.2	2.9	35.8	26.5	1.0	22.3	2.6	7.6	100.0
1978	1.2	2.8	35.1	26.9	1.0	22.9	2.6	7.5	100.0
1979	1.3	2.9	34.7	27.3	1.1	22.7	2.7	7.5	100.0
1980	1.3	3.0	33.7	28.7	1.0	22.4	2.7	7.1	100.0
1981	1.3	2.6	33.1	29.8	1.0	22.5	2.7	7.1	100.0
1982	1.4	2.5	31.6	31.3	1.0	22.2	2.8	7.2	100.0
1983	1.4	2.5	29.2	32.6	1.0	23.0	2.9	7.5	100.0
1984	1.5	2.7	29.3	32.5	0.9	23.0	2.8	7.3	100.0
1985	1.4	3.0	29.3	32.9	0.8	22.7	2.8	7.2	100.0
1986	1.4	3.0	29.2	32.8	0.9	22.7	2.9	7.2	100.0
1987	1.4	3.0	28.8	33.4	0.8	22.4	3.0	7.2	100.0
1988	1.3	3.2	28.8	33.2	0.9	22.6	3.0	6.9	100.0
1989	1.3	3.3	28.7	33.9	0.9	22.2	3.0	6.7	100.0
1990	1.2	3.8	28.4	33.8	0.9	21.8	3.1	6.9	100.0
1991	1.2	3.9	28.3	33.8	0.8	21.6	3.2	7.0	100.0
1992	1.2	4.1	27.4	34.3	0.8	21.8	3.3	7.1	100.0
1993	1.3	4.2	27.5	33.8	0.9	21.8	3.3	7.2	100.0
1994	1.3	4.3	28.0	33.5	0.9	21.9	3.3	7.0	100.0
1995	1.3	4.4	27.5	33.6	0.9	22.1	3.4	7.0	100.0
1996	1.2	4.7	26.5	33.9	0.8	22.3	3.5	7.0	100.0
1997	1.2	4.9	26.1	34.1	0.8	22.3	3.6	7.0	100.0
1998	1.2	4.9	25.9	35.4	0.8	21.4	3.6	6.8	100.0

Notes: AGR = agriculture, MNG = mining, MNF = manufacturing, EGW = electricity, gas and water, CNS = construction, TRS = transport, CMR = commercial, and RSD = residential.
Source: Bush *et al.* 1999. *Australian Energy: market developments and projections to 2014-15*, Australian Bureau of Agricultural and Resource Economics, Canberra.

Appendix Table A2.3 **Agriculture sector gross energy consumption by fuel, 1974-98**

Years	Electricity		Gas		Oil		Coal		Total
	PJ	%	PJ	%	PJ	%	PJ	%	PJ
1974	3.6	9.3%	0.0	0.0%	35.0	90.7%	0.0	0.0%	38.6
1975	3.9	9.8%	0.0	0.0%	35.5	90.2%	0.0	0.0%	39.3
1976	3.9	9.8%	0.0	0.0%	36.0	90.2%	0.0	0.0%	40.0
1977	4.2	10.1%	0.0	0.0%	37.1	89.9%	0.0	0.0%	41.2
1978	4.5	10.5%	0.0	0.0%	38.8	89.5%	0.0	0.0%	43.3
1979	4.4	9.7%	0.0	0.0%	40.6	90.3%	0.0	0.0%	44.9
1980	5.0	10.6%	0.0	0.0%	42.1	89.4%	0.0	0.0%	47.1
1981	5.3	10.8%	0.0	0.0%	43.6	89.2%	0.0	0.0%	48.8
1982	5.6	10.5%	0.0	0.0%	47.9	89.5%	0.0	0.0%	53.5
1983	6.2	12.5%	0.0	0.0%	43.5	87.5%	0.0	0.0%	49.7
1984	6.0	10.8%	0.0	0.0%	49.7	89.2%	0.0	0.0%	55.7
1985	6.5	11.8%	0.0	0.0%	48.3	88.2%	0.0	0.0%	54.7
1986	6.7	12.3%	0.0	0.0%	47.3	87.7%	0.0	0.0%	54.0
1987	7.0	12.4%	0.0	0.0%	49.4	87.6%	0.0	0.0%	56.4
1988	7.5	13.5%	0.0	0.0%	47.9	86.5%	0.0	0.0%	55.4
1989	7.6	12.9%	0.0	0.0%	50.9	87.1%	0.0	0.0%	58.4
1990	8.0	14.1%	0.0	0.0%	48.8	85.8%	0.0	0.0%	56.9
1991	8.5	14.7%	0.0	0.0%	49.2	85.3%	0.0	0.0%	57.7
1992	8.8	14.9%	0.0	0.0%	49.9	85.0%	0.0	0.0%	58.7
1993	9.0	14.8%	0.0	0.0%	51.7	85.2%	0.0	0.0%	60.6
1994	9.1	14.6%	0.0	0.0%	53.3	85.3%	0.0	0.0%	62.5
1995	9.4	14.6%	0.0	0.1%	55.0	85.3%	0.0	0.0%	64.4
1996	9.5	14.7%	0.0	0.0%	55.0	85.3%	0.0	0.0%	64.5
1997	9.7	14.5%	0.0	0.0%	57.4	85.7%	0.0	0.0%	67.0
1998	9.9	14.4%	0.0	0.0%	58.9	85.6%	0.0	0.0%	68.8

Note: PJ = peta joules.
Source: Bush *et al.* 1999. *Australian Energy: market developments and projections to 2014-15*, Australian Bureau of Agricultural and Resource Economics, Canberra.

Appendix Table A2.4 **Mining sector gross energy consumption by fuel, 1974-98**

Years	Electricity		Gas		Oil		Coal		Total
	PJ	%	PJ	%	PJ	%	PJ	%	PJ
1974	15.4	18.0%	13.4	15.6%	29.3	34.3%	27.4	32.0%	85.4
1975	16.5	18.2%	17.6	19.4%	29.6	32.8%	26.7	29.5%	90.3
1976	16.8	18.7%	20.3	22.6%	30.0	33.4%	22.8	25.3%	89.8
1977	17.7	18.0%	20.9	21.2%	35.0	35.6%	24.8	25.2%	98.3
1978	17.5	17.9%	20.2	20.6%	34.7	35.4%	25.6	26.1%	98.0
1979	17.7	17.2%	21.9	21.2%	36.5	35.4%	27.0	26.2%	103.2
1980	17.3	15.7%	24.2	21.9%	38.7	35.1%	30.1	27.3%	110.3
1981	18.0	18.6%	23.3	24.2%	29.1	30.1%	26.2	27.1%	96.6
1982	19.0	20.1%	25.5	27.0%	25.1	26.5%	24.9	26.3%	94.5
1983	19.5	21.0%	31.3	33.8%	23.2	25.0%	18.6	20.1%	92.6
1984	19.6	19.4%	39.0	38.6%	22.9	22.7%	19.5	19.3%	101.0
1985	21.1	18.2%	49.1	42.3%	24.5	21.1%	21.4	18.4%	116.2
1986	23.5	19.9%	47.7	40.4%	25.0	21.2%	21.8	18.5%	118.0
1987	24.4	19.6%	50.2	40.2%	27.7	22.2%	22.6	18.1%	124.8
1988	25.7	18.9%	59.0	43.3%	28.2	20.7%	23.4	17.2%	136.4
1989	30.1	20.5%	61.6	41.9%	33.2	22.6%	21.9	14.9%	146.9
1990	35.1	19.7%	81.0	45.4%	38.0	21.3%	24.2	13.6%	178.2
1991	35.6	19.4%	84.7	46.2%	39.0	21.3%	24.1	13.1%	183.3
1992	37.1	19.1%	90.9	46.7%	40.1	20.6%	26.5	13.6%	194.6
1993	38.1	18.7%	103.1	50.7%	42.3	20.8%	19.8	9.8%	203.3
1994	38.9	18.5%	105.4	50.2%	44.5	21.2%	21.3	10.1%	209.9
1995	41.4	18.1%	117.3	51.3%	47.2	20.6%	22.8	10.0%	228.7
1996	43.7	17.4%	130.3	52.0%	54.3	21.7%	22.2	8.9%	250.5
1997	44.3	16.8%	133.7	50.8%	61.2	23.2%	24.2	9.2%	263.4
1998	47.8	17.2%	146.3	52.6%	61.3	22.0%	22.8	8.2%	278.2

Note: PJ = peta joules.

Source: Bush *et al.* 1999. *Australian Energy: market developments and projections to 2014-15*, Australian Bureau of Agricultural and Resource Economics, Canberra.

Appendix Table A2.5 **Manufacturing sector gross energy consumption by fuel, 1974-98**

Years	Electricity		Gas		Oil		Coal		Total
	PJ	%	PJ	%	PJ	%	PJ	%	PJ
1974	87.6	7.3%	93.5	7.8%	382.2	31.8%	638.6	53.1%	1201.9
1975	88.4	7.2%	100.8	8.2%	359.2	29.2%	680.9	55.4%	1229.3
1976	90.1	7.4%	110.7	9.1%	357.9	29.6%	651.6	53.8%	1210.2
1977	94.9	7.8%	124.1	10.2%	375.0	30.7%	628.2	51.4%	1222.1
1978	97.8	8.0%	139.8	11.4%	369.9	30.2%	617.8	50.4%	1225.3
1979	103.5	8.3%	153.7	12.3%	351.1	28.2%	636.9	51.1%	1245.1
1980	109.9	8.9%	184.4	14.9%	330.2	26.7%	612.8	49.5%	1237.3
1981	115.4	9.4%	203.9	16.6%	294.6	24.0%	614.8	50.0%	1228.6
1982	118.0	9.8%	209.8	17.5%	265.8	22.2%	605.8	50.5%	1199.3
1983	116.5	11.0%	216.8	20.4%	221.2	20.8%	508.6	47.8%	1063.0
1984	133.6	12.1%	221.8	20.1%	244.1	22.1%	502.9	45.6%	1102.3
1985	147.1	12.7%	252.0	21.8%	228.6	19.8%	525.8	45.6%	1153.5
1986	155.6	13.4%	270.1	23.2%	217.2	18.7%	520.9	44.8%	1163.7
1987	163.7	13.8%	283.8	23.9%	215.4	18.2%	522.8	44.1%	1185.7
1988	177.6	14.5%	289.4	23.6%	230.9	18.8%	530.8	43.2%	1228.7
1989	190.6	14.7%	296.6	22.9%	237.1	18.3%	571.6	44.1%	1295.9
1990	196.7	14.9%	305.3	23.1%	232.0	17.6%	586.2	44.4%	1320.3
1991	197.7	15.0%	309.4	23.5%	235.5	17.9%	576.1	43.7%	1318.6
1992	199.7	15.5%	308.9	24.0%	230.6	17.9%	548.8	42.6%	1288.0
1993	206.3	15.6%	316.1	23.9%	244.8	18.5%	556.0	42.0%	1323.2
1994	215.3	15.6%	334.3	24.2%	249.2	18.0%	583.4	42.2%	1382.3
1995	215.7	15.3%	345.6	24.5%	256.6	18.2%	595.3	42.1%	1413.2
1996	214.8	15.3%	340.0	24.3%	258.6	18.5%	587.3	41.9%	1400.7
1997	221.3	15.7%	358.1	25.4%	224.3	15.9%	606.4	43.0%	1410.1
1998	238.8	16.3%	359.7	24.5%	228.5	15.6%	638.3	43.6%	1465.3

Note: PJ = peta joules.

Source: Bush *et al.* 1999. *Australian Energy: market developments and projections to 2014-15*, Australian Bureau of Agricultural and Resource Economics, Canberra.

Appendix Table A2.6 **E-G-W sector gross energy consumption by fuel, 1974-98**

Years	Electricity		Gas		Oil		Coal		Total
	PJ	%	PJ	%	PJ	%	PJ	%	PJ
1974	36.4	4.9%	45.9	6.2%	69.5	9.4%	585.4	79.4%	737.2
1975	39.8	5.1%	44.4	5.7%	67.2	8.7%	623.1	80.4%	774.5
1976	41.7	5.2%	50.5	6.3%	67.6	8.4%	641.0	80.0%	800.9
1977	47.1	5.2%	71.9	7.9%	63.0	6.9%	724.2	79.9%	906.1
1978	49.1	5.2%	78.6	8.4%	62.4	6.6%	749.8	79.8%	939.9
1979	53.3	5.4%	87.6	8.9%	63.5	6.5%	774.9	79.1%	979.2
1980	56.2	5.3%	98.8	9.4%	54.9	5.2%	846.5	80.1%	1056.4
1981	60.1	5.4%	128.1	11.6%	53.4	4.8%	864.7	78.2%	1106.2
1982	61.2	5.1%	154.1	12.9%	57.7	4.8%	917.4	77.1%	1190.4
1983	60.7	5.1%	141.6	11.9%	50.7	4.3%	932.6	78.7%	1185.6
1984	63.1	5.2%	148.0	12.1%	49.4	4.0%	961.4	78.7%	1221.9
1985	71.1	5.5%	135.5	10.4%	43.0	3.3%	1047.2	80.8%	1296.8
1986	71.8	5.5%	157.4	12.0%	37.5	2.9%	1041.0	79.6%	1307.7
1987	73.7	5.4%	151.9	11.1%	28.6	2.1%	1120.1	81.5%	1374.3
1988	72.4	5.1%	160.1	11.3%	23.2	1.6%	1161.0	82.0%	1416.6
1989	78.2	5.1%	162.8	10.6%	30.4	2.0%	1259.8	82.3%	1531.2
1990	79.1	5.0%	179.9	11.4%	40.7	2.6%	1273.6	81.0%	1573.2
1991	76.6	4.9%	137.6	8.7%	41.5	2.6%	1318.7	83.8%	1574.4
1992	80.7	5.0%	148.3	9.2%	29.8	1.8%	1353.9	84.0%	1612.7
1993	79.8	4.9%	151.6	9.3%	30.0	1.8%	1362.5	83.9%	1623.9
1994	80.7	4.9%	160.9	9.7%	30.0	1.8%	1379.8	83.6%	1651.5
1995	85.1	4.9%	181.7	10.5%	33.7	1.9%	1427.2	82.6%	1727.6
1996	85.9	4.8%	165.2	9.2%	34.5	1.9%	1505.3	84.1%	1790.9
1997	86.4	4.7%	161.8	8.8%	27.3	1.5%	1565.0	85.0%	1840.5
1998	92.5	4.6%	183.9	9.2%	25.8	1.3%	1699.5	84.9%	2001.7

Note: PJ = peta joules.

Source: Bush *et al.* 1999. *Australian Energy: market developments and projections to 2014-15*, Australian Bureau of Agricultural and Resource Economics, Canberra.

Appendix Table A2.7 **Construction sector gross energy consumption by fuel, 1974-98**

Years	Electricity		Gas		Oil		Coal		Total
	PJ	%	PJ	%	PJ	%	PJ	%	PJ
1974	0.1	0.3%	0.0	0.0%	25.8	99.7%	0.0	0.0%	25.9
1975	0.1	0.3%	0.0	0.0%	28.9	99.7%	0.0	0.0%	29.0
1976	0.1	0.3%	0.0	0.0%	28.8	99.7%	0.0	0.0%	28.9
1977	0.1	0.2%	0.0	0.1%	35.7	99.7%	0.0	0.0%	35.8
1978	0.1	0.2%	0.0	0.1%	35.3	99.7%	0.0	0.0%	35.4
1979	0.1	0.2%	0.0	0.1%	37.6	99.7%	0.0	0.0%	37.7
1980	0.1	0.2%	0.0	0.1%	38.2	99.7%	0.0	0.0%	38.3
1981	0.1	0.2%	0.0	0.1%	37.5	99.7%	0.0	0.0%	37.6
1982	0.1	0.2%	0.1	0.4%	38.8	99.4%	0.0	0.0%	39.0
1983	0.1	0.2%	0.2	0.4%	34.7	99.3%	0.0	0.0%	34.9
1984	0.1	0.2%	0.2	0.6%	33.0	99.1%	0.0	0.0%	33.3
1985	0.1	0.3%	0.3	0.8%	30.9	98.9%	0.0	0.0%	31.2
1986	0.1	0.3%	0.2	0.7%	34.4	99.0%	0.0	0.0%	34.7
1987	0.1	0.3%	0.2	0.7%	34.6	99.0%	0.0	0.0%	34.9
1988	0.1	0.3%	0.2	0.6%	39.1	99.1%	0.0	0.0%	39.4
1989	0.1	0.3%	0.2	0.6%	41.2	99.1%	0.0	0.0%	41.6
1990	0.1	0.3%	0.2	0.6%	40.7	99.1%	0.0	0.0%	41.1
1991	0.1	0.3%	0.2	0.6%	36.9	99.1%	0.0	0.0%	37.2
1992	0.1	0.3%	0.2	0.6%	38.9	99.1%	0.0	0.0%	39.3
1993	0.1	0.2%	0.3	0.6%	41.3	99.2%	0.0	0.0%	41.7
1994	0.1	0.3%	0.3	0.6%	42.7	99.2%	0.0	0.0%	43.1
1995	0.1	0.2%	0.3	0.6%	43.9	99.2%	0.0	0.0%	44.3
1996	0.1	0.2%	0.3	0.7%	43.5	99.1%	0.0	0.0%	43.9
1997	0.1	0.2%	0.3	0.7%	45.2	99.1%	0.0	0.0%	45.6
1998	0.1	0.2%	0.3	0.6%	46.6	99.1%	0.0	0.0%	47.0

Note: PJ = peta joules.

Source: Bush *et al.* 1999. *Australian Energy: market developments and projections to 2014-15*, Australian Bureau of Agricultural and Resource Economics, Canberra.

Appendix Table A2.8 **Transport sector gross energy consumption by fuel, 1974-98**

Years	Electricity		Gas		Oil		Coal		Total
	PJ	%	PJ	%	PJ	%	PJ	%	PJ
1974	2.5	0.4%	0.4	0.1%	682.2	99.5%	0.3	0.0%	685.4
1975	2.7	0.4%	0.3	0.0%	697.7	99.5%	0.3	0.0%	701.0
1976	2.7	0.4%	0.5	0.1%	711.5	99.5%	0.3	0.0%	714.9
1977	2.9	0.4%	1.2	0.2%	757.6	99.4%	0.3	0.0%	761.9
1978	2.9	0.4%	1.7	0.2%	793.9	99.4%	0.2	0.0%	798.7
1979	2.9	0.4%	1.6	0.2%	808.3	99.4%	0.2	0.0%	812.9
1980	3.2	0.4%	2.4	0.3%	818.9	99.3%	0.2	0.0%	824.6
1981	3.5	0.4%	2.8	0.3%	828.7	99.2%	0.2	0.0%	835.2
1982	3.4	0.4%	3.3	0.4%	836.9	99.2%	0.1	0.0%	843.8
1983	3.6	0.4%	4.0	0.5%	828.7	99.0%	0.7	0.1%	837.0
1984	4.0	0.5%	4.6	0.5%	851.9	98.6%	3.7	0.4%	864.1
1985	4.3	0.5%	4.5	0.5%	879.9	98.6%	3.4	0.4%	892.1
1986	4.7	0.5%	6.5	0.7%	891.8	98.4%	3.3	0.4%	906.3
1987	4.9	0.5%	4.5	0.5%	908.9	98.6%	3.8	0.4%	922.1
1988	5.5	0.6%	5.1	0.5%	951.8	98.5%	3.6	0.4%	966.0
1989	6.2	0.6%	5.0	0.5%	989.7	98.5%	4.0	0.4%	1004.9
1990	6.5	0.6%	5.2	0.5%	997.2	98.5%	3.5	0.3%	1012.5
1991	6.6	0.7%	4.7	0.5%	987.9	98.5%	3.7	0.4%	1003.0
1992	6.8	0.7%	5.5	0.5%	1008.0	98.4%	4.0	0.4%	1024.3
1993	6.8	0.6%	6.5	0.6%	1032.2	98.3%	4.1	0.4%	1049.6
1994	7.0	0.6%	7.8	0.7%	1061.6	98.3%	3.9	0.4%	1080.2
1995	7.2	0.6%	8.8	0.8%	1117.3	98.2%	4.0	0.4%	1137.2
1996	7.4	0.6%	9.3	0.8%	1160.9	98.2%	4.0	0.3%	1181.6
1997	7.7	0.6%	10.1	0.8%	1180.9	98.2%	4.3	0.4%	1203.0
1998	8.2	0.7%	10.8	0.9%	1187.5	98.1%	4.2	0.3%	1210.7

Note: PJ = peta joules.

Source: Bush *et al.* 1999. *Australian Energy: market developments and projections to 2014-15*, Australian Bureau of Agricultural and Resource Economics, Canberra.

Appendix Table A2.9 **Commercial sector gross energy consumption by fuel, 1974-98**

Years	Electricity		Gas		Oil		Coal		Total
	PJ	%	PJ	%	PJ	%	PJ	%	PJ
1974	33.8	42.2%	8.7	10.9%	29.3	36.6%	8.2	10.2%	80.1
1975	35.5	42.7%	10.6	12.7%	28.8	34.7%	8.1	9.8%	83.0
1976	37.8	44.5%	11.7	13.8%	27.5	32.5%	7.8	9.2%	84.8
1977	41.2	46.6%	13.3	15.1%	26.3	29.8%	7.6	8.6%	88.4
1978	44.1	48.9%	14.5	16.0%	24.3	26.9%	7.4	8.2%	90.2
1979	47.8	50.2%	16.8	17.6%	22.9	24.0%	7.7	8.1%	95.2
1980	52.2	52.5%	17.9	18.0%	21.9	22.0%	7.4	7.4%	99.5
1981	56.4	55.8%	19.2	18.9%	18.4	18.2%	7.2	7.1%	101.2
1982	59.2	56.6%	22.4	21.4%	16.0	15.3%	7.1	6.8%	104.7
1983	60.6	58.0%	23.9	22.9%	12.9	12.4%	7.1	6.8%	104.5
1984	62.0	58.7%	25.9	24.5%	10.8	10.2%	7.0	6.6%	105.7
1985	65.5	59.6%	27.5	25.0%	10.1	9.2%	6.8	6.2%	109.9
1986	70.5	60.7%	28.8	24.8%	10.1	8.7%	6.8	5.8%	116.2
1987	75.7	61.5%	30.8	25.1%	9.8	8.0%	6.7	5.4%	123.0
1988	81.8	63.2%	31.2	24.1%	10.0	7.7%	6.5	5.0%	129.5
1989	87.4	63.9%	32.4	23.7%	10.3	7.5%	6.6	4.8%	136.7
1990	93.8	64.4%	35.0	24.0%	10.5	7.2%	6.4	4.4%	145.6
1991	98.3	65.0%	36.0	23.8%	10.9	7.2%	6.0	4.0%	151.1
1992	99.7	64.6%	38.2	24.7%	11.2	7.3%	5.2	3.4%	154.4
1993	102.8	64.7%	39.6	24.9%	11.8	7.4%	4.7	3.0%	159.0
1994	105.9	65.2%	40.1	24.7%	12.0	7.4%	4.6	2.8%	162.5
1995	113.7	65.6%	43.2	24.9%	12.1	7.0%	4.3	2.5%	173.3
1996	123.3	66.0%	45.7	24.5%	12.5	6.7%	5.4	2.9%	186.9
1997	129.1	67.0%	46.3	24.0%	12.4	6.4%	4.8	2.5%	192.6
1998	136.0	67.4%	48.5	24.0%	12.8	6.3%	4.5	2.2%	201.8

Note: PJ = peta joules.

Source: Bush *et al.* 1999. *Australian Energy: market developments and projections to 2014-15*, Australian Bureau of Agricultural and Resource Economics, Canberra.

Appendix Table A2.10 **Residential sector gross energy consumption by fuel, 1974-98**

Years	Electricity		Gas		Oil		Coal		Total
	PJ	%	PJ	%	PJ	%	PJ	%	PJ
1974	71.1	30.7%	31.2	13.5%	45.9	19.8%	83.0	35.9%	231.3
1975	79.6	32.3%	35.5	14.4%	51.9	21.1%	79.2	32.1%	246.3
1976	83.6	33.9%	36.8	14.9%	50.9	20.7%	74.8	30.4%	246.4
1977	91.2	35.0%	43.2	16.6%	55.1	21.2%	70.5	27.1%	260.2
1978	95.5	36.6%	45.6	17.5%	50.4	19.3%	69.1	26.5%	261.0
1979	101.5	37.5%	49.8	18.4%	49.2	18.2%	69.3	25.6%	270.5
1980	104.3	39.8%	51.3	19.6%	35.8	13.7%	69.7	26.6%	261.9
1981	109.8	41.8%	55.1	21.0%	26.7	10.2%	70.2	26.7%	262.8
1982	115.2	42.2%	61.4	22.5%	24.6	9.0%	70.3	25.8%	272.8
1983	116.4	42.6%	63.3	23.2%	21.5	7.9%	70.5	25.8%	273.2
1984	117.5	42.6%	66.0	23.9%	20.0	7.3%	70.6	25.6%	276.0
1985	119.9	42.5%	69.5	24.6%	19.8	7.0%	70.9	25.1%	282.1
1986	124.1	43.0%	72.9	25.3%	18.0	6.2%	70.9	24.6%	288.4
1987	128.0	42.9%	78.3	26.3%	17.9	6.0%	71.5	24.0%	298.1
1988	130.2	44.0%	75.7	25.5%	16.5	5.6%	71.5	24.1%	296.2
1989	131.9	43.7%	78.6	26.1%	16.1	5.3%	72.6	24.1%	301.5
1990	138.8	43.0%	90.0	27.9%	16.6	5.1%	74.6	23.2%	322.3
1991	141.3	43.1%	91.0	27.8%	16.5	5.0%	76.7	23.4%	327.8
1992	141.5	42.3%	95.0	28.4%	16.9	5.1%	78.7	23.5%	334.6
1993	146.3	42.2%	99.5	28.7%	18.0	5.2%	81.0	23.3%	347.1
1994	146.0	42.4%	97.6	28.3%	16.5	4.8%	81.9	23.8%	344.5
1995	151.8	42.3%	106.1	29.6%	16.2	4.5%	82.1	22.9%	358.6
1996	155.5	42.1%	112.3	30.4%	15.9	4.3%	82.4	22.3%	369.4
1997	161.2	42.7%	113.7	30.1%	15.9	4.2%	83.2	22.0%	377.4
1998	167.4	43.5%	115.7	30.1%	15.5	4.0%	82.3	21.4%	384.6

Note: PJ = peta joules.
Source: Bush *et al.* 1999. *Australian Energy: market developments and projections to 2014-15*, Australian Bureau of Agricultural and Resource Economics, Canberra.

3

The structure of consumer energy demand: three applications of the almost ideal demand system

Synopsis

The Almost Ideal (AI) demand system is parameterised in this chapter, both as an autoregressive error model (AREM) and as a vector error correction model (VECM), with a view to studying the structure of consumer energy demand in Australia. To this end, domestic per person energy use is divided into the consumption of electricity, gas and a miscellaneous category, residual fuels. The AREM is estimated using national-level annual data while the VECM representation is applied to national-level quarterly data. The AREM-based results suggest that the three fuels may be net substitutes, but gross complements. The national-level quarterly data based VECM model, in contrast, finds significant substitution possibilities, both net and gross, between electricity and other fuels and between gas and other fuels but strong complementarity between electricity and gas. The last application, which applies the static AI model to quarterly panel data from the mid-1980s to 1998 when energy prices were relatively stable, finds significant substitution possibilities between gas and other fuels only. The cross-price elasticities between electricity and gas are positive but not significant.

3.1 Introduction

Despite having significant policy implications for issues ranging from competition policy to environmental management, residential energy demand and, more precisely, the estimation of demand elasticities for the various energy sources has not attracted much attention in Australia. Not only is the literature on the subject very limited but also electricity consumption has been the focus of attention.[1] Hawkins (1975), for instance, employed single equation methods to estimate the demand for electricity in the Australian Capital Territory (ACT) and New South Wales (NSW). Donnelly (1984) and Donnelly and Diesendorf (1985) also estimated an electricity demand function for the ACT using single equation procedures. A number of other studies, which belong to this class of specification and estimation, have modelled electricity demand but only as a part of an aggregate measure of electricity (see, for instance, Donnelly and Saddler 1984; Stromback 1986).

Rushdi (1986), on the other hand, has modelled the interrelated demand for electricity, natural gas and heating oils in South Australia using a translog demand system. However, to the best of this author's knowledge, no study, at least in the recent past, has made an attempt to determine inter-fuel substitution possibilities at the national level using a systems approach. The objective of this study is to fill this gap. To this end, domestic per person energy use is divided into the consumption of electricity, gas and a miscellaneous category, residual fuels. Deaton and Muellbauer's (1980) Almost Ideal (AI) demand system, which is probably the most extensively employed system among the family of flexible consumer demand systems, is chosen to represent the structure of interrelated consumer demand.

This chapter reports three different applications of the AI demand system. These are discussed very briefly in the following paragraphs, as it will help to explain the underlying reason for this repetition. In the first exercise, the static AI demand system is applied to national-level annual data for the period 1970 to 1998, given the assumption that the vector of stochastic errors follows an autoregressive pattern of order one. Weak separability is invoked, due primarily to the limited number of observations. The Marshallian cross-price elasticities estimated are largely negative, although not all are significant. It is argued that mis-specified dynamics, among other factors, led to these unexpected findings.

The next set of results reported are drawn from an exercise in which adjustment is modelled, although in an implicit fashion. The AI model is parameterised as a vector error correction model (VECM), assuming the AI model represents the steady-state structure of consumer behaviour. This AI/VECM methodology is applied to national-level quarterly data for the period from the third quarter 1969 to the second quarter 1998. The system is closed by treating all other household expenditure as another demand variable. Significant substitution possibilities – both net and gross – are found between electricity and other fuels and between gas and other fuels. However, the cross-price elasticities between electricity and gas are still negative and, this time, highly significant, implying that the two fuels are net and gross substitutes. It is hypothesised that the limited availability of gas and a relatively stable electricity-gas price ratio are responsible for this unexpected outcome.

The problem of the gas supply constraint can possibly be controlled for by way of pooling a cross-section of different states and by introducing regional dummies in the estimating equations. Access to reticulated gas is high in some Australian states such as Victoria and South Australia, and low in others including Queensland and Tasmania. By pooling the state-level data and introducing state-dummies, it was hoped to obtain theoretically correct signs of the two elasticities. Further, the introduction of a cross-sectional dimension brings an additional source of price variation and probably more variation in the electricity/gas price ratio, and thus a better probability of obtaining theoretically correct signs of the two cross elasticities. The third and final exercise reported implements this idea by way of applying a static AI model and AI/VECM approach to time-series data consisting of a panel of five states.[2] The data set spans the period from the third quarter 1984 to the second quarter 1998.

However, only the static AI model results are reported as the estimates of parameters and elasticities based on the dynamic model are largely insignificant. This analysis finds significant substitution possibilities between gas and other fuels but the other inter-fuel substitution elasticities, both Hicksian and Marshallian, are not significant although the cross-price elasticities between electricity and gas are positively signed. In fact, the period of the late 1980s and 1990s is characterised by relatively stable energy prices. Therefore, there is very limited information in the data set as far as substitution possibilities are concerned.

3.2 Methodology

3.2.1 Econometric model

As mentioned above, the AI model is assumed to be the steady-state structure of consumer preferences. It is appropriate, therefore, to derive the estimating equations of this system before moving on to the discussion of an autoregressive model and an appropriate dynamic specification. Following Deaton and Muellbauer (1980), it is assumed that consumer preferences are represented by the following PIGLOG (price-independent, generalised logarithmic) specification of an expenditure function:

$$\log c(u,P) = (1-u)\log[a(P)] + u\log[b(P)] \tag{3-1}$$

where u denotes a utility level; P is a vector of prices; c represents minimum consumption required to attain u given P; and *log* stands for a natural logarithm. $\log[a(P)]$ and $\log[b(P)]$ which are termed by the authors as the cost of subsistence and bliss, respectively, are defined as:

$$\begin{aligned} \log a(P) &= \alpha_0 + \sum_i \alpha_i \log p_i + 1/2\sum_i\sum_j \gamma_{ij}^* \log p_i \log p_j + \sum_i \lambda_i \log p_i t \\ \log b(P) &= \log a(P) + \beta_0 \Pi_i p_i^{\beta_i} \end{aligned} \tag{3-2}$$

where t is a simple time trend which is included with a view to capturing the biases, if any, in the progress of energy consumption technology.[3] Substituting (3-2) into (3-1) the PIGLOG expenditure function is written as:

$$\begin{aligned} \log c(u,P) = \alpha_0 &+ \sum_i \alpha_i \log p_i + 1/2\sum_i\sum_j \gamma_{ij}^* \log p_i \log p_j + \\ &\sum_i \lambda_i \log p_i t + u\beta_0 \Pi_i p_i^{\beta_i} \end{aligned} \tag{3-3}$$

For this expenditure function to be linearly homogenous in prices the following restrictions on the parameters are required:

$$\sum_i \alpha_i = 1, \quad \sum_i \gamma_{ij}^* = \sum_j \gamma_{ij}^* = \sum_j \beta_j = \sum_j \lambda_j = 0 \tag{3-4}$$

Applying Shephard's lemma to the expenditure function in (3-3) gives the familiar demand system (in share form) of the AI model:

$$w_i = \alpha_i + \sum_j \gamma_{ij} \log p_j + \beta_j \log(x/P) + \lambda_j t \tag{3-5}$$

where w_i is the expenditure share of commodity i; x/P is total per capita real expenditure on 'n' goods and P is a price index defined as:

$$\log P = \alpha_0 + \sum_i \alpha_i \log p_i + 1/2\sum_i\sum_j \gamma_{ij} \log p_i \log p_j \tag{3-6}$$

and

$$\gamma_{ij} = (\gamma_{ij}^* + \gamma_{ji}^*)/2 \tag{3-7}$$

Equations (3-4) and (3-7) imply restrictions on the demand system depicted in (3-5). These restrictions can be re-written as a set of three equations:

$$\begin{aligned} &\sum_i \alpha_i = 1, \quad \sum_i \gamma_{ij} = \sum_i \beta_i = \sum_i \lambda_i = 0 \\ &\sum_j \gamma_{ij} = 0, \\ &\gamma_{ij} = \gamma_{ji} \end{aligned} \tag{3-8}$$

These restrictions are known as the 'adding-up', homogeneity of degree zero in prices and income, and symmetry conditions, respectively. The demand system as given in (3-5) is non-linear in parameters. In order to linearize the system, Deaton and Muellbauer's (1980) procedure is followed to approximate P by Stone's geometric price index:

$$\log P \cong \sum_i w_i \log(p_i) \tag{3-9}$$

The resulting demand system is known as the linear approximate AI demand system.[4] In the next two sub-sections estimating equations of an autoregressive error model and a fully dynamic model are derived. The introduction of autoregressive errors significantly complicates the estimation procedures due largely to the singularity of the system. This matter is given considerable attention in the following sub-section. The case for a vector error correction model is developed first in the next sub-section before specifying an appropriate VECM specification.

3.2.1.1 Autoregressive error model. In order to facilitate the derivation of an autoregressive error model, the system in (3-5) is written, using matrix notation, as:

$$W_{(t)} = \Pi X_{(t)} + V_{(t)} \tag{3-10}$$

where $W_{(t)}$ is an $n \times 1$ matrix of expenditure shares; $X_{(t)}$ is a $k \times 1$ matrix of explanatory variables including a unit variable; Π is an $n \times k$ matrix of unknown parameters; and $V_{(t)}$ is an $n \times 1$ vector of random disturbances which are assumed to be stationary. Following Berndt and Savin (1975), it is assumed that the vector of stochastic disturbances, $V_{(t)}$, follows a first order autoregressive pattern of the form:

$$V_{(t)} = RV_{(t-1)} + \xi_{(t)} \tag{3-11}$$

where R is a matrix of unknown parameters and $\xi_{(t)}$ is a vector of disturbance variables which are assumed to be independently and identically distributed normal random variables with mean vector zero and covariance matrix Ω. The singular nature[5] of the demand system in (3-10) implies:

$$\iota'\Pi = \begin{bmatrix}1 & 0 & 0......0\end{bmatrix} \tag{3-12}$$

and

$$\iota' V_{(t)} = 0 \tag{3-13}$$

where ι is an $n \times 1$ vector of ones. The singularity of the system also implies:

$$\iota' R = K' \text{ (a vector of constants)} \tag{3-14}$$

that is each column sum of the R matrix must equal the same (unknown) parameter. The singularity of the system further implies:

$$\iota' \xi_{(t)} = 0 \tag{3-15}$$

The singularity of the demand system, therefore, results in strong restrictions on the elements of R. More precisely, restrictions in (3-14) mean that each column sum of R must be the same, unknown, constant number. In the context of a diagonal R matrix, for instance, this implies that the first order autocorrelation coefficient across all n equations is the same.

One equation in the autoregressive model presented in (3-10) and (3-11) is, indeed, redundant due again to the singularity of the system. After arbitrarily dropping the nth equation, the system becomes:

$$W_{(t)}^n = \Pi_n X_{(t)} + V_{(t)}^n \tag{3-16}$$

$$V_{(t)}^n = R_n V_{(t-1)} + \xi_t^n \tag{3-17}$$

where $W_{(t)}^n, V_{(t)}^n$ and ξ_t^n are the vectors $W_{(t)}, V_{(t)}$ and $\xi_{(t)}$ with the last variable deleted and Π_n and R_n are the Π and R matrices with the nth row deleted. The above system cannot be estimated as R_n is not a square matrix. The matrix can, however, be transformed into a square matrix and thus usual maximum likelihood (ML) procedures can be used to estimate the appropriately transformed system. Following Berndt and Savin (1975), the stochastic difference system (3-11) is written, using (3-13), as:

$$V_{(t)} = \overline{R} V_{(t-1)}^n + \xi_{(t)} \tag{3-18}$$

where

$$\overline{R} = \begin{bmatrix} R_{11} - R_{1n} & R_{12} - R_{1n} & \dots & R_{1,n-1} - R_{1n} \\ R_{21} - R_{2n} & R_{22} - R_{2n} & \dots & R_{2,n-1} - R_{2n} \\ . & . & \dots & . \\ . & . & \dots & . \\ R_{n1} - R_{nn} & R_{n2} - R_{nn} & \dots & R_{n,n-1} - R_{nn} \end{bmatrix} \tag{3-19}$$

It is worth noting that each column sum of $\overline{R}$ equals zero. In order to proceed further, the nth variable from the $V_{(t)}$ and $\xi_{(t)}$ vectors is dropped, along with the nth row of $\overline{R}$ to get:

$$V_{(t)}^{n} = \overline{R}_n V_{(t-1)}^{n} + \xi_{(t)}^{n} \qquad (3\text{-}20)$$

Clearly $\overline{R}_n$ is a square matrix so (3-16) in combination with (3-20) constitutes a system that can be estimated using the ML estimation procedures mentioned previously. This autoregressive model, (3-16) and (3-20), maintains the invariance property as the estimates of Π_n, $\overline{R}_n$ and Ω_n are not sensitive to which equation is deleted from the system. However, R is not identified, as individual elements of R are not estimable from elements of $\overline{R}_n$ unless exogenous identifying restrictions are imposed on elements of R.[6] The estimating system, which is obtained by manipulating (3-16) and (3-20), is given by:

$$W_{(t)}^{n} = \overline{R}_n W_{(t-1)}^{n} + \Pi_n X_{(t)} + \overline{R}_n \Pi_n X_{(t-1)} + \xi^{n}{}_{(t)} \qquad (3\text{-}21)$$

The above system is estimated, as mentioned previously, using annual data for the period 1970 to 1998, giving a total of 29 data points. It is further assumed that energy demand is weakly separable from the other commodities. This assumption is invoked largely due to a small number of observations because the number of unknown parameters rises sharply with the introduction of another commodity. The explanatory variables, therefore, are price indices of electricity, gas and other fuels and per capita total expenditure on energy. The resulting demand equations for electricity, gas and other fuels are known as conditional or second stage demand functions in the literature.[7] The underlying linear approximate AI structure is, therefore, given by:

$$\begin{aligned} w_1 &= \alpha_1 + \gamma_{11} \log p_1 + \gamma_{12} \log p_2 + \gamma_{13} \log p_3 + \beta_1 \log(x/P^*) + \lambda_1 t \\ w_2 &= \alpha_2 + \gamma_{21} \log p_1 + \gamma_{22} \log p_2 + \gamma_{23} \log p_3 + \beta_2 \log(x/P^*) + \lambda_2 t \\ w_3 &= \alpha_3 + \gamma_{31} \log p_1 + \gamma_{32} \log p_2 + \gamma_{33} \log p_3 + \beta_3 \log(x/P^*) + \lambda_3 t \end{aligned} \qquad (3\text{-}22)$$

where 1 = electricity; 2 = gas; 3 = other fuels; x = per capita (nominal) expenditure on energy; and P^* is Stone's geometric price index as defined previously. Progress in energy consumption technology is said to be ith energy saving (consuming) if λ_i is negative (positive). Technical progress is said to be neutral if λ_i is zero. Similarly, ith energy is considered to be necessity (luxury) if β_i is negative (positive). And, finally, the underlying preferences are homothetic rather than non-homothetic if all β coefficients are simultaneously zero in the above system.

There are 18 unknown parameters in the above system in the absence of symmetry conditions. This number, however, reduces to 15 after accounting for the restrictions implied by the symmetry property ($\gamma_{12} = \gamma_{21}$, $\gamma_{13} = \gamma_{31}$ and $\gamma_{23} = \gamma_{32}$). The adding-up restrictions further help express the symmetry restrictions as follows:

$$\begin{aligned} \gamma_{12} &= \gamma_{21} \\ \gamma_{13} &= -(\gamma_{11} + \gamma_{12}) \\ \gamma_{23} &= -(\gamma_{12} + \gamma_{22}) \end{aligned} \tag{3-23}$$

The number of free parameters in the steady-state system reduces further to nine after completely accounting for the restrictions implied by the adding-up property.

3.2.1.2 Dynamic model. A number of approaches have been developed to introduce dynamics in the context of a demand system. Considine and Mount (1984), for instance, suggested procedures to introduce dynamic adjustments in the context of linear logit models.[8] Pollak and Wales (1992) suggested two methods, dynamic translating and dynamic scaling, to add a dynamic structure to any demand system.[9] Muellbauer and Pashardes (1992) introduced a dynamic version of the AI model by incorporating habit and durability into the utility function. This study, following Anderson and Blundell (1982), incorporates dynamics in the context of a system using a general approach rather than employing a specific theory of dynamic adjustment. More precisely, the static AI model is imagined as the underlying steady-state representation of commodity demand, and dynamics are added to this long term relationship by parameterising the steady-state system as a vector error correction model (VECM). Anderson and Blundell (1982) suggested this approach a long time before the popularization of modern time-series techniques of cointegration and unit roots.[10]

The underlying steady-state structure is discussed before moving to an appropriate VECM representation. The starting point, again, is the system given in (3-5). However, to close the model, non-energy household expenditure is taken as the fourth variable because of the relatively long time series to which this methodology is applied.[11] The steady-state structure of the model, therefore, includes the following system of four equations:

$$\begin{aligned} w_1 &= \alpha_1 + \gamma_{11}\log p_1 + \gamma_{12}\log p_2 + \gamma_{13}\log p_3 + \gamma_{14}\log p_4 + \beta_1 \log(x/P^*) \\ w_2 &= \alpha_2 + \gamma_{21}\log p_1 + \gamma_{22}\log p_2 + \gamma_{23}\log p_3 + \gamma_{24}\log p_4 + \beta_2 \log(x/P^*) \\ w_3 &= \alpha_3 + \gamma_{31}\log p_1 + \gamma_{32}\log p_2 + \gamma_{33}\log p_3 + \gamma_{34}\log p_4 + \beta_3 \log(x/P^*) \\ w_4 &= \alpha_4 + \gamma_{41}\log p_1 + \gamma_{42}\log p_2 + \gamma_{43}\log p_3 + \gamma_{44}\log p_4 + \beta_4 \log(x/P^*) \end{aligned} \tag{3-24}$$

where 1 = electricity; 2 = gas; 3 = other fuels; 4 = all other goods; x = per capita total (nominal) expenditure; and P^* is Stone's geometric price index as defined previously. The trend variable is not included in this specification as in earlier estimations of the specification the associated parameters were mostly insignificantly estimated and its inclusion made many other parameter estimates insignificant. Three quarterly dummy variables are also included among the set of regressors as the analysis employs quarterly data. The fourth quarter is taken as the base quarter. In the context of panel data, four state dummies are added in addition to three quarterly dummy variables.

There are 24 unknown parameters in the above system in the absence of symmetry conditions (dummy variable coefficients are not included in this count). This number, however, reduces to 18 after accounting for the restrictions implied by the symmetry property ($\gamma_{12} = \gamma_{21}$, $\gamma_{13} = \gamma_{31}$, $\gamma_{14} = \gamma_{41}$, $\gamma_{23} = \gamma_{32}$, $\gamma_{24} = \gamma_{42}$, $\gamma_{34} = \gamma_{43}$) The adding-up restrictions further help express the symmetry restrictions as follows:

$$\begin{aligned}
\gamma_{12} &= \gamma_{21} \\
\gamma_{13} &= \gamma_{31} \\
\gamma_{23} &= \gamma_{32} \\
\gamma_{14} &= -(\gamma_{11} + \gamma_{12} + \gamma_{13}) \\
\gamma_{24} &= -(\gamma_{12} + \gamma_{22} + \gamma_{23}) \\
\gamma_{34} &= -(\gamma_{3} + \gamma_{23} + \gamma_{33})
\end{aligned} \tag{3-25}$$

The number of free parameters in the steady-state system reduces further to 12 after completely accounting for the restrictions implied by the adding-up property.

Empirical estimates based on aggregate time-series data quite often reject the symmetry and homogeneity restrictions. The violation of these fundamental economic postulates is due, according to Anderson and Blundell (1982), to the fact that proper attention is not paid to the dynamic structure of the models. This hypothesis is considered in this study by testing the symmetry conditions given in (3-8), taking both the static and the dynamic models as maintained hypotheses.

In order to facilitate the derivation of a VECM representation, the system in (3-24) is written, using matrix notation, as:

$$W_{(t)} = \Gamma Z_{(t)} \tag{3-26}$$

where $W_{(t)}$ is a 4×1 vector of expenditure shares; $Z_{(t)}$ is a $k \times 1$ matrix of explanatory variables which includes a unit variable and seasonal dummies (and state dummies in the case of panel data) and Γ is a $4 \times k$ matrix of the steady-state parameters. For the purposes of this study, the following specification of the VECM is proposed:

$$\Delta_4 W_{(t)} = A\Delta_4 \widetilde{Z}_{(t)} - B(W^{n}_{(t-4)} - \Gamma_n Z_{(t-4)}) + \zeta_{(t)} \tag{3-27}$$

where Δ_4 is defined as $\Delta_4 y_t = y_t - y_{t-4}$ (y_t is an auxiliary variable) which reflects the fact that the specification will be applied to quarterly data; A and B are the matrices which consist of short-run parameters; ~ implies that the intercept and the seasonal dummies are excluded from the matrix Z; n reflects that the last element of the W and Γ matrices is deleted due to the singular nature of the system; and $\zeta_{(t)}$ is a matrix of disturbance terms which are assumed to be independently and identically distributed normal variables. This specification has an interesting economic meaning. It allows consumers to adjust their consumption expenditure in response to new information on the explanatory variables as well as in response to the observed deviation from the steady-state equilibrium.

It is desirable to test the restrictions implied by the different models which are nested in this dynamic specification. Three such formulations are tested. The first is an autoregressive error model, which has been discussed in the previous sub-section. The system is written as:

$$\begin{aligned} W_{(t)} &= \Gamma Z_{(t)} + \omega_{(t)} \\ \omega_{(t)} &= \Phi\, \omega_{(t-4)} + \zeta(t) \end{aligned} \tag{3-28}$$

where Φ is 4×4 matrix of unknown parameters. The second formulation is the partial adjustment model of the following type:

$$\Delta_4 W_{(t)} = C(\Gamma Z_{(t)} - W_{(t-4)}) + \zeta_{(t)} \tag{3-29}$$

Nadiri and Rosen (1969) suggested this formulation and used it to study interrelated factor demands for US manufacturing. This procedure, which is essentially a generalisation of Koyck's single equation adjustment mechanism, permits dis-equilibrium in one commodity market to affect the demand for other commodities. Finally, the static model:

$$W_{(t)} = \Gamma Z_{(t)} + \zeta_{(t)} \tag{3-30}$$

is also considered as a special case of the dynamic formulation in (3-27). This static representation assumes instantaneous adjustment and thus the estimated elasticities are interpreted as the long-run elasticities.

3.2.2 Demand elasticities

For the linear approximate AI model, the Hicksian own-price (δ_{ii}) and cross-price elasticities (δ_{ij}) can be computed from:

$$\delta_{ii} = -1 + \gamma_{ii} / w_i + w_i, \qquad i = 1,2,........,n \tag{3-31}$$

$$\delta_{ij} = \gamma_{ij} / w_i + w_i, \qquad i,j = 1,2,.........,n; \;\; i \neq j \tag{3-32}$$

The above elasticity estimates and, more precisely, the sign of δ_{ij} will help determine the nature of the relationship between the different forms of energy. A positive sign implies they are substitutes and a negative sign indicates that they are complements to each other. The uncompensated own-price elasticities (ε_{ii}) and cross-price elasticities (ε_{ij}) are obtained from:

$$\varepsilon_{ii} = -1 + \gamma_{ii} / w_i - \beta_i, \qquad i = 1,2,.........,n \tag{3-33}$$

$$\varepsilon_{ij} = \gamma_{ij} / w_i - \beta_i (w_j / w_i), \qquad i,j = 1,2,..........,n; \;\; i \neq j \tag{3-34}$$

A positively (negatively) signed ε_{ij} implies, on the other hand, that the two fuels are gross substitutes (complements). Finally, the expenditure elasticities (η_i) are estimated from:

$$\eta_i = 1 + \beta_i / w_i, \qquad i = 1,2,............,n \tag{3-35}$$

It should be noted that the predicted shares are employed in the estimation of the above elasticities along with the estimates of the $\gamma_{ij}s$ and βs. Further, because parameter estimates and predicted cost shares have variances and covariances, the elasticity estimates have stochastic disturbances as well. Since the elasticities are non-linear functions of parameter estimates and fitted cost shares, the standard errors cannot be calculated exactly. In order to obtain approximate standard errors the predicted expenditure shares are treated as fixed.[12] The variances of the elasticity estimates are, therefore, computed from:

$$\begin{aligned}
&V(\delta_{ij}) = V(\gamma_{ij}) / w_i^2 \\
&V(\delta_{ii}) = V(\gamma_{ii}) / w_i^2 \\
&V(\varepsilon_{ii}) = V(\gamma_{ii}) / w_i^2 + V(\beta_i) - 2Cov(\gamma_{ii}, \beta_i) / w_i \\
&V(\varepsilon_{ij}) = V(\gamma_{ij}) / w_i^2 + V(\beta_i)(w_j^2 / w_i^2) - 2Cov(\gamma_{ij}, \beta_i)(w_j / w_i^2) \\
&V(\eta_i) = V(\beta_i) / w_i^2
\end{aligned} \tag{3-36}$$

where V stands for variance and Cov indicates covariance. The estimated variances of the estimated γ_{ij} and β parameters and fitted cost shares are used while obtaining estimates of the above variances.

3.3 Data and estimation

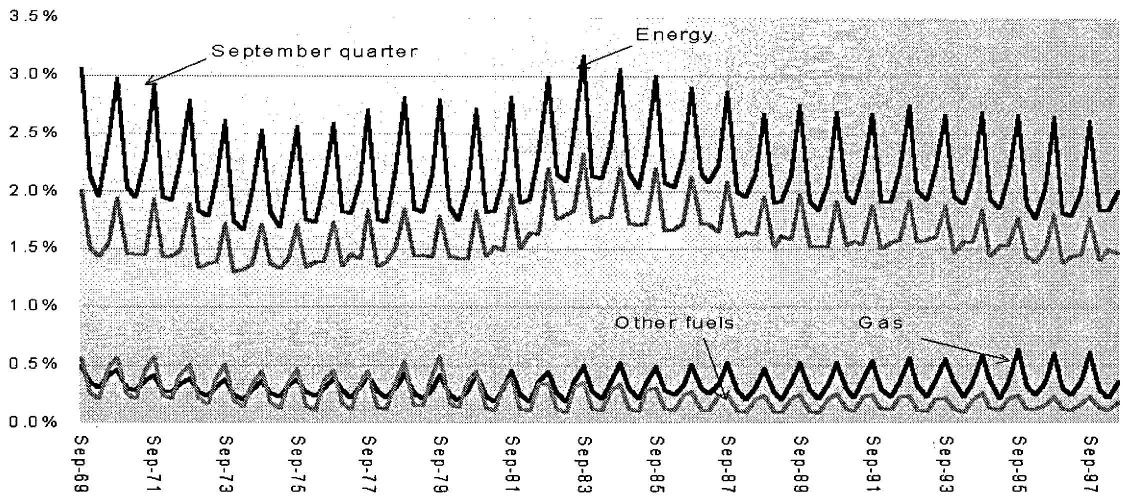
The data used for the various estimations are both annual and quarterly – seasonally unadjusted – and are drawn from various Australian Bureau of Statistics (ABS) publications. The autoregressive model is estimated using national-level annual data for the period 1970 to 1998 that is, 29 data points. The AI/VECM is applied once to national-level quarterly data spanning the period from the third quarter 1969 to the second quarter 1998 and then to a panel of five states. The panel data covers the period from the third quarter 1984 to the second quarter 1998 for each of the five states.

Total household consumption expenditure, household expenditure on energy, and population were obtained from various issues of the 'Australian National Accounts: National Income, Expenditure and Product' (ABS Catalogue No. 5206.0) and the 'Australian National Accounts: Quarterly State Details' (ABS Catalogue No. 5206.0.40.001). Both nominal and constant values of expenditure at 1990 prices were obtained. The break-up of the energy category into expenditure on electricity, gas and other fuels was also obtained from the Bureau on request, as these data are not published. The price deflators were constructed by dividing the nominal variables by the corresponding real ones.

However, in the case of the panel data, current price data on individual fuels is available only from the third quarter 1989 whereas the constant dollar data begin from the third quarter 1984. With a view to utilizing the constant price data for the period from the third quarter 1984 to the second quarter 1989, national-level prices of the three fuels are used to obtain current dollar fuel consumption data. This procedure gives 100 additional observations, 20 for each of the five states. An illustration of the national-level data set is presented in Figures 3.1 and 3.2.

The expenditure shares of the three energy sources along with the total energy expenditure share are plotted in Figure 3.1. The total energy expenditure share has fluctuated significantly around an average (entire-period) share of 2.2 per cent during the last three decades, primarily due to seasonal factors. The share peaks in the third quarter, the coldest quarter because of a significant increase in the consumption of electricity, gas and other fuels, and also due to the relatively low non-energy consumption during this period. The share falls sharply during the fourth quarter and to a lower level during the first quarter, although the downward movement in the share from the fourth quarter to the first quarter is relatively minor. This systematic pattern of fluctuations holds for the entire period with a few exceptions.

Figure 3.1 **Energy expenditure shares** (per cent)

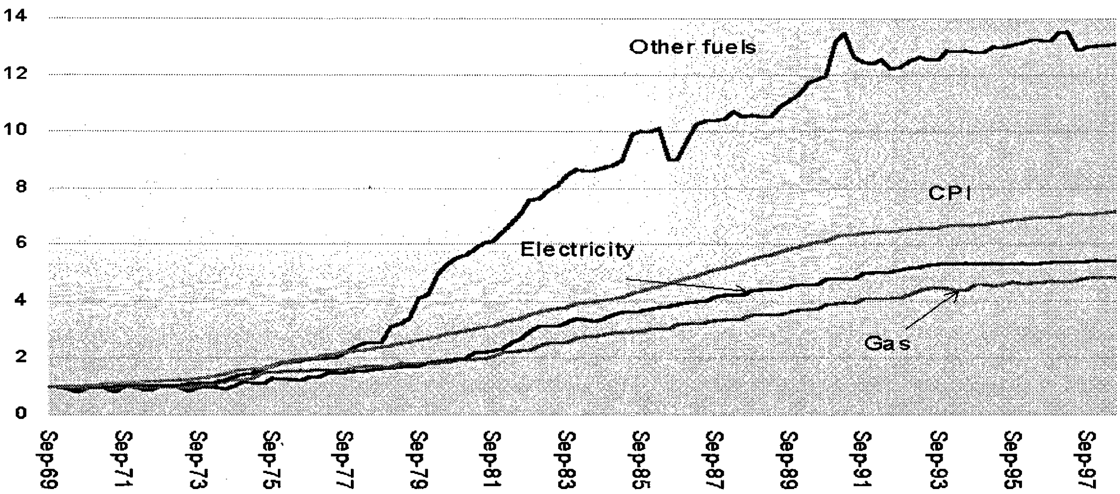


Sources: Australian Bureau of Statistics, 1999. *Australian National Accounts: national income, expenditure and product*, Catalogue No. 5206.0, Canberra; author's calculations.

Electricity, which accounts for almost 74 per cent of total energy consumption expenditure, has more or less the same seasonal pattern. Its average share of total household expenditure seems to have increased from around 1.5 per cent in the early 1970s to as high as 2 per cent during the late 1980s, primarily at the expense of the other fuels. A declining trend in this variable is obvious during the 1990s, with the share of electricity in overall consumption expenditure falling back to the level of the 1970s. The share of other fuels has fallen in a cyclical fashion to almost 0.25 per cent in 1997 from around 0.5 per cent in 1969, mainly due to a substantial increase in the real price of this variable, which occurred mostly during the 1980s. Natural gas, on the other hand, has increased its share considerably during the last two decades.[13]

The average price level for the household sector increased by a factor of seven during this period of almost three decades (Figure 3.2). The nominal prices of gas and the other fuels increased by a factor of less than six. The real prices of electricity and natural gas, as a consequence, declined by 16 per cent and 30 per cent, respectively. The relative price of the residual energy category, on the other hand, almost doubled as the nominal price of this fuel increased by a factor of roughly 14 during this period due primarily to the rising petroleum product prices.

Figure 3.2 **Price indices, energy and average consumer price**



Sources: Australian Bureau of Statistics, 1999. *Australian National Accounts: national income, expenditure and product,* Catalogue No. 5206.0, Canberra; author's calculations.

From this study's point of view, however, it is of more interest to compare the price path of one energy category with the others because a significant relative price change is crucial to being able to make robust estimates of the substitution possibilities between the different energy categories. Electricity and gas prices grew at roughly the same rate up until the late 1970s. The electricity price index, however, rose relative to that of natural gas at the beginning of the next decade. The gap between the two indices has subsequently diminished owing to a slow down in electricity price inflation during the last eight years or so. The price of the residual fuels has not only fluctuated substantially but has also increased very significantly relative to the other energy prices.

Most of the price increases in energy, and in the household expenditure items more generally, occurred between 1978 and 1991, triggered by the second oil price shock. Almost 84 per cent of the other fuels price rise, for instance, occurred during this period. The price index of the non-energy category is not graphed because it is almost perfectly described by the consumer price index, due to the overwhelming proportion of the non-energy expenditure in total household consumption expenditure.

A brief description of the panel data is depicted in Table 3.1. The expenditure shares of individual fuels as a percentage of total household energy expenditure along with the share of non-energy expenditure as a percentage of total household expenditure are presented in the first two columns for two quarters, the second quarter 1985 and the second quarter 1998. The corresponding price indices are given in the last two columns.[14] The electricity expenditure share dominates the other two fuel expenditure shares in each of the five states. This is especially true in the case of New South Wales and Queensland. Queenslanders, for instance, spent less than 10 per cent of their total energy expenditure on gas and other fuels during the second quarter 1998. In South and Western Australia, in contrast, approximately three quarters of total energy expenditure is spent on electricity. Energy consumption patterns are quite different in Victoria where the share of electricity in total energy expenditure is closer to one-half and that of gas is roughly one-third.

Table 3.1 **Statewide expenditure shares and price indices across five states** (per cent)

States/Variables	Expenditure shares		Price indices	
	2nd quarter1985	2nd quarter1998	2nd quarter1985	2nd quarter1998
NSW				
❑ Electricity	83.96	84.63	100	144
❑ Gas	6.18	8.78	100	165
❑ Other fuels	9.86	6.59	100	155
❑ Non-energy*	98.01	98.31	100	172
Victoria				
❑ Electricity	56.32	54.43	100	172
❑ Gas	29.97	34.75	100	171
❑ Other fuels	13.71	10.82	100	134
❑ Non-energy*	97.08	97.37	100	167
Queensland				
❑ Electricity	89.60	91.45	100	134
❑ Gas	3.40	2.14	100	147
❑ Other fuels	7.00	6.41	100	132
❑ Non-energy*	97.95	98.42	100	168
South Australia				
❑ Electricity	73.49	72.03	100	150
❑ Gas	15.99	16.08	100	171
❑ Other fuels	10.52	11.89	100	121
❑ Non-energy*	97.45	97.67	100	165
Western Australia				
❑ Electricity	74.42	71.86	100	145
❑ Gas	9.59	19.76	100	137
❑ Other fuels	15.99	8.38	100	136
❑ Non-energy*	97.57	97.88	100	172

Note: * - The price index is the consumer price index and not the non-energy price index.
Sources: Australian Bureau of Statistics, 1999. *Australian National Accounts – quarterly state details,* Catalogue No. 5206.0.40.001, Canberra; author's calculations.

Energy expenditure shares have generally not moved much during the past 14 years or so. In the case of Western Australia, however, the share of gas doubled and that of other fuels almost halved. Energy price inflation has generally been lower than the consumer price inflation. As a result, the three fuels were usually cheaper in the second quarter 1998 as compared with the second quarter 1985. In NSW, for example, electricity was cheaper, in a real sense, by 17 per cent, other fuels by 10 per cent and gas by 4 per cent in the second quarter 1998 compared to the second quarter 1985.

For the purposes of estimating the autoregressive model, the residual fuel share equation is arbitrarily dropped and the remaining two equations are estimated simultaneously in SHAZAM using the non-linear seemingly unrelated regression procedure. The estimates of parameters, log-likelihood values, and standard deviations are invariant to the choice of which three equations are directly estimated.[15] All parameters of the residual fuel share equation are recovered with the help of demand system restrictions. The redundancy problem in the case of AI/VECM is avoided by dropping the non-energy expenditure share equation and estimating the three fuel equations simultaneously.

3.4 Results

3.4.1 Autoregressive error model/annual data

Parameter estimates of the autoregressive error model for the Australian household sector, 1970 through 1998, are presented in Appendix Table A3.1. In earlier estimations of the model, results of which are not reported here, the restrictions of the static model (3-22) and those of adding-up and symmetry (3-23) were tested in two steps. Initially, the autoregressive model (3-21) and the corresponding static model (3-22) were estimated without imposing the restrictions of adding-up and symmetry. Based on the likelihood ratio test, the static model was rejected at the 1 per cent level of significance. In the second step, the autoregressive model was re-estimated after incorporating the adding-up and symmetry properties. These restrictions could not be rejected even at the 10 per cent level of significance using the likelihood ratio test. The parameter estimates in Appendix Table 3.1 correspond to the autoregressive model that incorporates the adding-up and symmetry restrictions.

A cursory look at the table reveals that most of the parameters are estimated with a reasonable degree of precision. Only five out of a total of 19 estimated parameters are not distinguishable from a value of zero at the 5 per cent level. Included in this group of parameters are an intercept term, α_2, the coefficient of the expenditure variable in the gas demand equation, β_2, the coefficient of the trend variable in electricity demand function, λ_1, and an element of the $\overline{R}_n$ matrix, $\bar{r}_{21}$. There is one price coefficient, γ_{23}, which is also included in this class of insignificant parameter estimates. The remaining three elements of the 2×2 matrix $\widetilde{R}_n$ are highly significant. Indeed, the hypotheses of no serial correlation and of a diagonal R are rejected at the 1 per cent level.

The value of generalised R-square, $\widetilde{R}^2$, is almost unity, implying that the null hypothesis of slope coefficients in all equations simultaneously being zero is rejected quite easily.[16] Individual R^2s are also fairly high, implying that the predicted expenditure shares follow very closely the corresponding actual expenditure shares over the estimation period.

The hypothesis of unbiased progress in energy consumption technology is easily rejected. The value of the likelihood ratio test statistic is 79.53 while the critical value at the 1 per cent level of significance and two degrees of freedom is 9.21. The development in energy consumption technology during the last three decades is, therefore, not unbiased. Clearly, it has enhanced the consumption of gas and helped reduce the use of other fuels as the respective coefficients are statistically significant. But, it is difficult to say whether the technical change has been electricity-consuming as the coefficient is not significant although it has a positive sign.

Similarly, the restrictions of homothetic preferences are rejected at the 1 per cent level. The computed value of the LR test statistic is 15.31 while the corresponding critical value, again, is 9.21. The coefficient of the expenditure (income) variable has a negative sign in the first two equations but a positive one in the last equation. Electricity and gas consumption are, therefore, classified as necessities while other fuels are classed as a luxury by the data set given, of course, the AI methodology. The claim regarding gas, however, is a bit fragile as the respective coefficient is not significant.

For the underlying expenditure function to be (globally) quasi-concave in commodity prices, the Slutsky substitution matrix – the matrix of compensated demand derivatives – must be negative semidefinite at each point in time. This condition is satisfied if the eigenvalues of the Slutsky matrix are non-positive over the entire time period. Unfortunately, there are frequent violations of the condition; it is not satisfied even at the sample means. However, the own-price elasticities – both Hicksian and Marshallian – are negatively signed over the entire sample range.[17]

The estimates of the Hicksian and Marshallian elasticities evaluated at the mean predicted shares are reported in Table 3.2 along with approximate t-values.[18] The compensated cross-price elasticities are positive and statistically significant at the 10 per cent level in the case of electricity-gas and gas-other fuels, implying that electricity-gas and gas-other fuels are substitutes. The corresponding elasticities between electricity and other fuel are not significant. The Marshallian cross-price elasticities are, however, all negative with the exception of ε_{23} and they are significant at least at the 10 per cent level in two-thirds of the cases, implying that electricity-gas and electricity-other fuels may be gross complements.

Table 3.2 **Autoregressive error model, demand elasticities at the means**

Hicksian (compensated) elasticities

Quantity	P_1	P_2	P_3	Expenditure
h_1	-0.0848***	0.0503***	0.0345	na
	(1.88)	(1.72)	(1.20)	na
h_2	0.2433***	-0.4159*	0.1726*	na
	(1.72)	(3.60)	(2.85)	na
h_3	0.2361	0.2444*	-0.4805*	na
	(1.20)	(2.85)	(3.02)	na

Marshallian (uncompensated) elasticities

Quantity	P_1	P_2	P_3	Expenditure
q_1	-0.6909*	-0.0701**	-0.0540***	0.8199*
	(9.66)	(2.17)	(1.84)	(10.01)
q_2	-0.2331	-0.5143*	0.1031***	0.6444**
	(1.42)	(3.59)	(1.62)	(2.60)
q_3	-1.7874*	-0.1739	-0.7759*	2.7372*
	(4.91)	(1.37)	(4.60)	(5.89)

Note: *-Significant at the 1 per cent level, ** significant at the 5 per cent level, *** significant at the 10 per cent level.

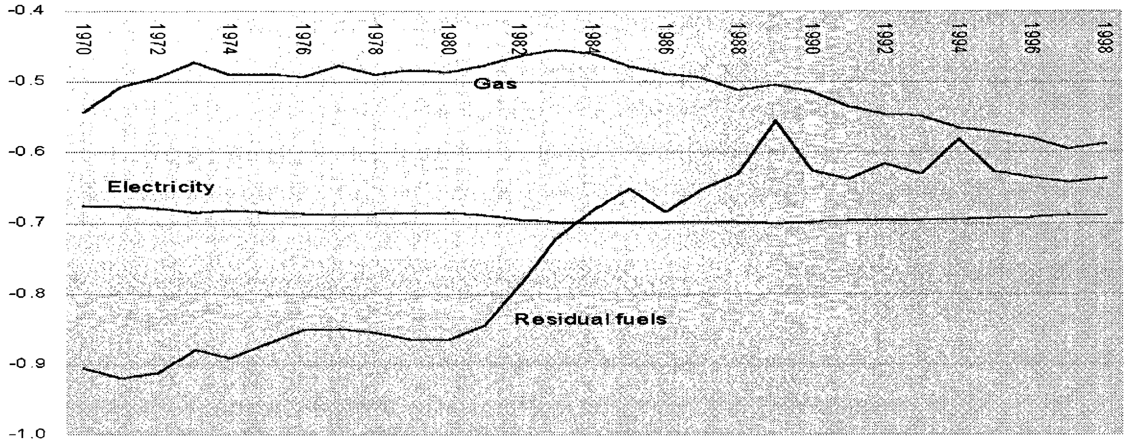
Source: Author's estimations.

The reversal of sign suggests that the substitution effect is relatively small and that the income effect associated with a price change more than offsets the usual substitution effect. This is an unexpected finding. It is known that natural gas is a good substitute for electricity in the areas of cooking and space and water heating. Similarly, the other fuel category, which consists primarily of heating oils and wood, along with some minor components such as coal, is also a substitute for electricity and gas in some respects. Further, the income variation associated with a price change is not expected to be sizeable because energy consumption is only a small fraction of total household expenditure, a little more than 2 per cent in 1997.

One possible explanation of this apparently unexpected finding might be the mis-specification of dynamics in the model. The existence of strong autocorrelation in the static version of the model supports this hypothesis.[19] A dynamic demand system seems, on theoretical grounds, to be a superior candidate to represent the energy demand structure as compared with a static one because of the relatively long life of energy appliances. Someone may prefer to switch to, say, gas from electricity for cooking and heating purposes after a relative price change but may not find it economical to do so instantaneously because of the electrical appliances installed. So, this unexpected finding may very well be the result of a model mis-specification. This is a hypothesis which needs to be tested before drawing any conclusions regarding the extent of inter-fuel substitution in the sector. Application of a different (static) demand system such as a translog or logit system or single equation methods could be another procedure undertaken before establishing any such conclusion, as results may differ quite significantly across functional specifications.[20]

The uncompensated own-price elasticities, which are reported in Table 3.2 and plotted in Figure 3.3, are all less than unity in absolute terms, implying that the demand for electricity, gas and other fuels is price inelastic. Furthermore, electricity and gas consumption is a necessity while other fuels are a luxury. The international literature on consumer energy demand is generally in favour of price-elastic electricity and gas demand and mixed on the size of the corresponding income elasticity estimates (see Donnelly 1984; Al-Sahlawi 1989; and Rothman *et al.* 1994).[21] The existing Australian literature on electricity demand modeling, on the other hand, has consistently shown the demand for electricity to be price inelastic. Interestingly, the magnitude of the estimates is quite similar to the present estimates.[22] However, there is very little evidence concerning the elasticity estimates of gas demand in Australia. Rushdi (1986) found the demand for gas and oil to be price elastic for the residential sector of South Australia.

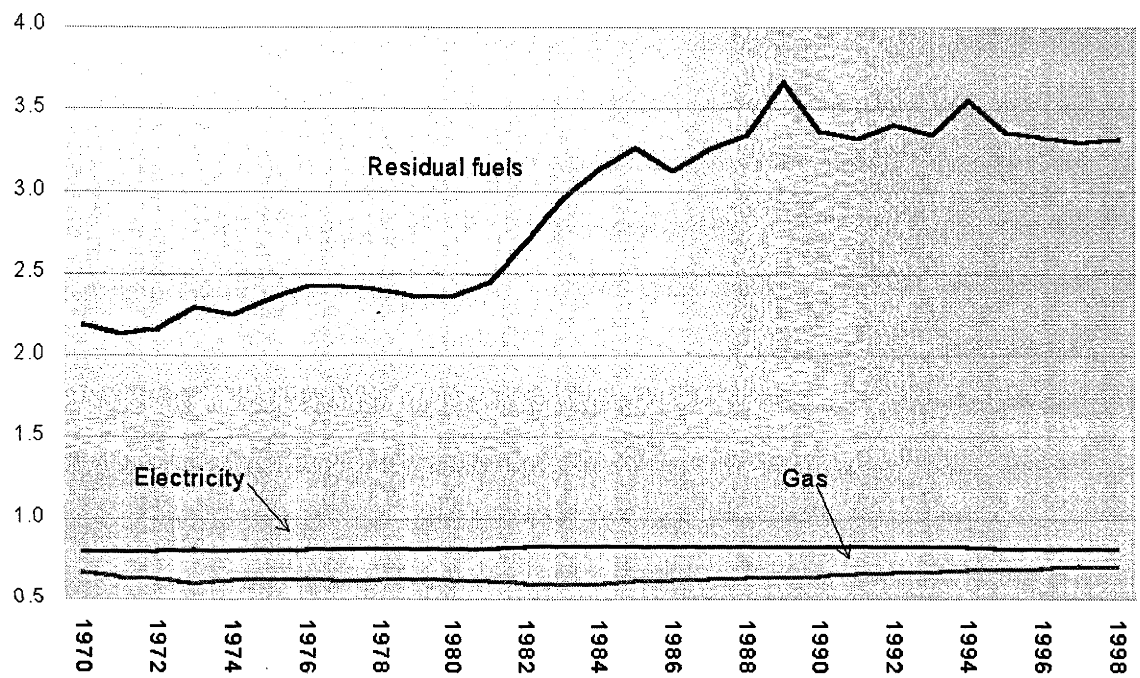
Figure 3.3 **Autoregressive error model, own-price elasticities**



Source: Author's estimations.

The income elasticity of residual category is not only quite high but also has increased over the years (Figure 3.4). The income sensitivity of the fuel, which was less than 2.5 during the early 1970s, increased to around 3.5 during the late 1980s and the early 1990s due probably to the second oil shock that hit the economy during the late 1970s. In contrast, the income elasticities of the other two fuels – electricity and gas, which are classified as necessary fuels – are very stable, especially that of electricity.

Figure 3.4 **Autoregressive error model, income elasticities**



Source: Author's estimations.

3.4.2 Vector error correction model/quarterly data

Before moving on to the main body of results, the results from cointegration and unit root analysis should be presented. The unit root results for the four residuals, which are obtained by estimating the static AI model, are given in the lower part of Table 3.3. The unit root statistics show that the null hypothesis of a unit root is consistently rejected even after accounting for the fact that the co-integrating vector is unknown. The table also contains the unit root statistics performed on the main variables of the model. As expected, the expenditure shares are all stationary because the shares are bounded. Total household expenditure is also stationary in the sense that it has no stochastic trend. The four price variables, on the other hand, are I(1) as they become stationary after differencing once.

Table 3.3 **Unit root analysis using the Phillips-Perron procedure**

Variables	Level	First-differenced
w_1	-9.654	-19.001
w_2	-10.178	-11.253
w_3	-10.298	-10.852
w_4	-10.810	-13.548
$\log(p_1)$	-1.153	-13.453
$\log(p_2)$	-0.729	-10.260
$\log(p_3)$	0.675	-8.259
$\log(p_4)$	2.767	-5.207
$\log(x/P)$	-11.872	-20.209
Res_1	-5.340	..
Res_2	-8.120	..
Res_3	-7.400	..
Res_4	-7.270	..

Notes: 1.The unit root analysis takes into consideration the quarterly nature of the data by incorporating quarterly dummy variables. 2. The 5 per cent critical t-test value for the residuals is 4.71 and the corresponding 1 per cent critical value for the usual variables is 3.96.
Source: Author's estimations.

The results pertaining to the restrictions implied by homogeneity, autoregressive error, partial adjustment and the static models are reported in Table 3.4. The maximised value of the (log) likelihood function in the absence of any restrictions is 2247.89. The symmetry restrictions when imposed reduce this value to 2243.93. Clearly, the symmetry conditions are not rejected even at the 10 per cent level of significance. It is interesting to note that these conditions are rejected at the 1 per cent level when the static model is taken as the unrestricted model. The dynamic model with symmetry imposed, therefore, is taken as the maintained model.

Table 3.4 **Tests of various models**

Numbe r	Model	log L	Test	LR test value	DF	CV 1%
1	Dynamic (No Symmetry)	2247.89	..	..	..	..
2	Dynamic (Symmetric)	2243.93	2v1	7.92	6	16.8
3	Autoregressive error	2211.30	3v2	65.25	15	30.6
4	Partial Adjustment	2201.89	4v2	84.07	15	30.6
5	Static	2105.48	5v2	276.91	24	43.0

Notes: 1. v stands for versus. 2. LR stands for likelihood ratio. 3. DF denotes degrees of freedom and CV 1 per cent means critical value at the 1 per cent level of significance.
Source: Author's estimations.

Both the autoregressive error model and the partial adjustment model impose 15 restrictions on the parameters of the symmetric dynamic model. Clearly, the restrictions are not the same as is evident from the different log L values. These restrictions are rejected with overwhelming support from the data. The static model, which imposes 24 restrictions on the structure of the maintained model, is also rejected very decisively.

The regression results reported in the first two columns of Appendix Table A3.2 correspond to the dynamic model, which incorporates the restrictions of homogeneity and symmetry. The results from the static AI model are also reported in the last two columns for the sake of comparison. The short-run parameters are omitted due mainly to space limitations and also because individual (short-run) parameters lack economic interpretation of any significance. Most of the steady-state parameters are estimated to be quite significant. Out of the six insignificant steady-state parameters, two are actually intercept terms. Two income coefficients, β_2 and β_3, are also insignificantly estimated. The sign of these coefficients, however, is not changed under the dynamic specification relative to the static one where these parameters are estimated very precisely.

The coefficient of the income/expenditure variable is negative in the electricity share equation and positive in the corresponding equation for the non-energy expenditure, implying that electricity is a necessity and the composite good a luxury. It would, however, be a too strong a conclusion to say that gas is a necessity and the other fuels a luxury, as the respective coefficients are not significant, although they are quite significant in the static model.

A significant upward shift in the shares of the three fuels during the third quarter relative to the fourth quarter (the base quarter in this model specification) is obvious, as the respective coefficients associated with the third quarter dummy are positive and highly significant. The second quarter dummy also picks up an upward shift in the energy expenditure shares. The degree of shift, however, is relatively minor due to the fact that the second quarter is a warmer period. The summer factor, which is captured by the first quarter dummy, seems to have no significant impact on the shares of electricity and the other fuels as the respective dummy coefficients are not significant.

The underlying expenditure function frequently violates the curvature restrictions. However, it is strictly quasi-concave at the sample means, as the eigenvalues associated with the Slutsky matrix are all negative. The elasticities reported below are evaluated at the sample means.

The top panel of Table 3.5 reports the Hicksian price elasticities along with the t-scores. The diagonal elements in these four columns are the own-price elasticities and the off diagonal ones are the cross-price elasticities. Out of a total of 16 elasticity estimates, three are not significant at the 5 per cent level. The cross-price elasticities between the different energy categories on the one hand and the composite good, non-energy consumption, on the other, are all positive and mostly significant, implying that energy and non-energy consumption are substitutes. The two consumption categories may be gross complements as the corresponding Marshallian elasticities reported in the lower part of the table are all negative, although mostly insignificant.

Table 3.5 **Demand elasticities at the means, quarterly data**

Hicksian elasticities

Quantity/Price	P_1	P_2	P_3	P_4	Expenditure
h_1	-0.6321*	-0.1789*	0.1727*	0.6383*	na
	(6.20)	(3.28)	(4.05)	(6.78)	na
h_2	-0.8717*	-0.5846	0.7092*	0.7472***	na
	(3.28)	(1.52)	(2.96)	(1.83)	na
h_3	1.2013*	1.0122*	-2.3087*	0.0952	na
	(4.05)	(2.96)	(4.70)	(0.26)	na
h_4	0.0106*	0.0026***	0.0002	-0.0134*	na
	(6.78)	(1.83)	(0.26)	(6.07)	na
Marshallian elasticities					
q_1	-0.6450*	-0.1816*	0.1709*	-0.1365	0.7922*
	(6.35)	(3.33)	(4.00)	(1.08)	(14.00)
q_2	-0.8854*	-0.5874	0.7072*	-0.0719	0.8375**
	(3.34)	(1.53)	(2.94)	(0.13)	(2.18)
q_3	1.1848*	1.0088*	-2.3110*	-0.8924	1.0098
	(3.98)	(2.96)	(4.69)	(0.97)	(1.25)
q_4	-0.0057*	-0.0008	-0.0021**	-0.9953*	1.0040*
	(3.66)	(0.58)	(2.40)	(350.32)	(712.25)

Note: *-Significant at the 1 per cent level, ** significant at the 5 per cent level, *** significant at the 10 per cent level.
Source: Author's estimations.

The (Marshallian) demand for the composite good is almost unit elastic with respect to both income and own-price, indicating the dominance of this commodity in the demand system. Electricity demand is price and income inelastic, which is consistent with the existing Australian literature on electricity demand estimation.[23] The corresponding two gas elasticities are fairly similar in terms of magnitudes; however, the price elasticity is not significant. The demand for the residual fuels, which are dominated by wood and heating oils, is highly price elastic but unit income inelastic. Also, the income elasticity is not distinguishable from zero in a statistical sense.

Note that the cross-price elasticities – both compensated and uncompensated – between electricity and the residual fuels and between gas and the residual fuels are not only positive but also highly significant. This is somewhat contrary to what was obtained from the first order autoregressive error model using annual data, where generally, negative (uncompensated) cross-price elasticities between the above-mentioned variables and also between electricity and gas were obtained.

The cross-price elasticities between electricity and gas are still negative and are significant at the 1 per cent level. Ironically, the corresponding Hicksian elasticities are also negatively signed with a high t-score, whereas previously these were positive. This is a disturbing sign, as the two sources of energy appear to be good substitutes in the areas of cooking and space and water heating. The single most important determinant of the sign of the above-mentioned elasticities is the sign of the γ_{12} parameter, which is negative in this case and has remained negative in the face of different experiments.[24]

There could be two, perhaps complementary, explanations of the complementary relationship between the fuels. The first is a supply-side explanation. Traditionally, electricity has been the main source of energy for the residential sector, followed by the residual category. The development of natural gas fields during the late 1960s provided a new source of energy. Although the gas transmission and reticulation system has expanded significantly over time, a substantial fraction of homes is still not connected to the grids.[25] The consumers without a gas connection are expected to differ in their response to, say, a relative fuel price change from those consumers with connections to gas supplies. The distortion created by the absence of this factor from the demand analysis might have resulted in the complementary relationship between electricity and gas.[26]

The other explanation is a demand-side one. The electricity price has increased relative to that of gas during the past 30 years by around 20 per cent. It seems, however, that the price increase has not been sufficient to push a significant fraction of households to gas consumption. The relative price remained almost stable during the 1970s, increased by around 23 per cent during the next decade and declined consistently at an average annual rate of around 1 per cent during the 1990s. Relatively slow expansion of the gas transmission and reticulation system and a lack of enthusiasm on the part of households caused by a relatively stable electricity-gas price ratio is expected to have resulted in this unusual finding.

3.4.3 Static AI model/panel data

Estimates of parameters, their approximate standard errors and t-scores are presented in Appendix Table A3.3 along with some overall goodness of fit statistics. There are a total of 42 parameter estimates out of which eight are statistically insignificant at the 10 per cent level. Three are price parameters, γ_{12}, γ_{13}, and γ_{22}, two are income parameters, β_3 and β_4, along with two quarterly dummy variables, δ_{21} and δ_{41}, and an intercept term, α_3. Predicted expenditure shares track closely the actual shares as the individual R^2s are fairly high, between 0.85 and 0.90. Moreover, there are no traces of autocorrelation as the DWs are very close to a value of two, reflecting no serial correlation. However, the underlying expenditure function violates the curvature condition quite frequently. The expenditure function is not quasi-concave even at the sample means, although own-price elasticities, both Hicksian and Marshallian, possess theoretically correct signs.

An examination of the results reveals that most of the variation in expenditure shares is attributable to state-specific and seasonal factors, as state and quarterly dummies are highly significant. This is explained in Table 3.6 where significance of different groups of variables is tested using the Wald-Chi-Square test. The null of no effect is rejected in each of the four groups of variables, including the two groups of prices and income/expenditure.

Table 3.6 **Some diagnostics**

Null	Wald	DF	Wald/DF	Critical Wald 5%
All $\delta_{ij} = 0$	1570.4	9	174.5	16.9
All $S_{ij} = 0$	1706.8	12	142.2	21.0
All $\gamma_{ij} = 0$	168.6	6	28.1	12.6
All $\beta_i = 0$	47.2	3	15.7	7.81

Note: δ_{ij} s are the coefficients of quarterly dummy variables and S_{ij} s are the coefficients of the state dummy variables and β_i s are as defined previously in (3-24).
Source: Author's estimations.

However, of greater interest in this table is the value of the Wald test statistic deflated by the corresponding degrees of freedom (shown in the column headed Wald/DF). The value of the Wald test per degree of freedom is highest in the case of quarterly dummy variables followed by the state dummies. It falls very sharply in the case of the remaining two groups. This shows very clearly that state-specific factors and the seasonal factors are the most important determinants of expenditure shares. The role of prices and income is relatively minor, probably because prices have remained relatively stable during this period of roughly one and a half decades.

The estimates of the demand elasticities that correspond to the panel data are reported in Table 3.7. The absolute values of the elasticities, especially those not relating to the non-energy good, are usually lower in absolute terms than the ones reported in Table 3.5 which are estimated using national-level quarterly data. This is probably because energy prices have been quite stable during the last 14 years and energy prices have declined in most of the states. Moreover, relative energy prices did not move much between 1985 and 1998 whereas during the late 1970s and early 1980s the prices of other fuels more than doubled relative to electricity and gas prices. Also, the estimates of the (Marshallian) own-price elasticities for electricity and other fuels are lower than the estimates based on annual data and the autoregressive error model (Table 3.2). The gas price elasticity is higher in the present estimates but it is not significant even at the 10 per cent level.

Note that the cross-price elasticities – both compensated and uncompensated – between electricity and gas are positively signed. However, these coefficients are not significant although the t-scores are greater than unity. Indeed γ_{12} – the parameter which plays a crucial role in determining the signs of the above-mentioned elasticities – is positively signed only in this set of results and not in the two previous ones. This supports the claim made previously, although very weakly, that panel data provides a way to account for the gas supply limitations and produce theoretically correct signs of the two elasticities.

Significant substitution possibilities – both net and gross – are found between gas and other fuels. However, the two cross-price elasticities between electricity and gas are negative although insignificant. Indeed, the inter-fuel substitution elasticities are mostly insignificant in this set of estimates. Again, this may reflect the fact that relative energy prices have not moved much during this period and thus did not provide an incentive to switch to relatively cheaper fuels.

Table 3.7 **Demand elasticities at the means, panel data**

Hicksian elasticities

Quantity/Price	P_1	P_2	P_3	P_4	Expenditure
h_1	-0.3388*	0.1082	-0.0294	0.2600*	na
	(3.60)	(1.34)	(1.19)	3.84	na
h_2	0.7318	-1.0240	0.6564*	-0.3642	na
	1.34	1.52	3.74	0.57	na
h_3	-0.2984	0.9838*	-0.4069*	-0.2785	na
	1.19	3.74	2.79	1.06	na
h_4	0.0056*	-0.0012	-0.0006	-0.0038	na
	3.84	0.57	1.06	1.34	na

Marshallian elasticities

q_1	-0.3531*	0.1061	-0.0309	-0.4105*	0.6884*
	(3.78)	(1.31)	(1.25)	(4.22)	(13.89)
q_2	0.6827	-1.0313	0.6516*	-2.6568*	2.3538*
	(1.25)	(1.53)	(3.72)	(3.37)	(5.33)
q_3	-0.3228	0.9802*	-0.4093*	-1.4178	1.1696*
	(1.30)	(3.73)	(2.82)	(1.58)	(6.55)
q_4	-0.0153*	-0.0042**	-0.0026*	-0.9798*	1.0020*
	(10.63)	(2.08)	(4.74)	(274.81)	(538.12)

Note: *-Significant at the 1 the per cent level, ** significant at the 5 per cent level, *** significant at the 10 per cent level.
Source: Author's estimations.

As far as the relationship between different fuels and non-energy consumption expenditure is concerned, electricity and non-energy good are net substitutes. The other four compensated cross-price elasticities characterising the relationship between gas, other fuels and non-energy consumption are insignificant, although negatively signed. The corresponding Marshallian elasticities are all negative and highly significant, implying gross complementarity in the consumption of the three fuels and the composite good, which is hardly surprising as non-energy consumption constitutes approximately 98 per cent of total household consumption expenditure. Fuel consumption, especially demand for gas and other fuels, is quite sensitive to variations in non-energy prices. Income and own-price elasticities of the non-energy good are almost unity, due again to the sheer size of this commodity.

3.5 Conclusions

Energy demand for electricity, gas and residual fuels for domestic cooking, heating and lighting in Australia was modelled and estimated by parameterising the Almost Ideal (AI) demand system as an autoregressive error model and a vector error correction model. To this end, domestic per person energy use was divided into the consumption of electricity, gas and a miscellaneous category, residual fuels. The autoregressive model was applied to the national-level annual data for the period 1970 to 1998. This model invoked weak separability and included, among the set of regressors, the prices of the three fuels, total (per capita) household energy expenditure, and a simple time trend.

The error correction model was applied to two different data sets. In one application, national-level quarterly data for the period from the third quarter 1969 to the second quarter 1998 was employed. The other application used a panel of five states, New South Wales, Victoria, Queensland, Western Australia and South Australia, to estimate consumer energy demand structure. All other household expenditure was introduced in these applications as another demand variable to close the system. As a consequence, the explanatory variables in the four-equation demand system were the four price indices and total (per capita) household consumption expenditure. Apart from the above-mentioned variables, three quarterly dummy variables were included in the set of regressors in the first of the two applications. The second employed four state dummies in addition to three quarterly dummy variables.

For the purposes of estimation, the residual fuel expenditure share (non-energy expenditure share equation) was arbitrarily dropped from the autoregressive model (error correction model) and the remaining two (three) equations were estimated by employing a non-linear, iterative, seemingly-unrelated regression procedure. Regression results and estimates of elasticities that correspond to the panel data-based error correction model were not reported as the parameters were largely insignificant and elasticity estimates mostly implausible. Instead, the corresponding static model results were presented. The underlying expenditure function frequently violated the curvature properties; however, the reported own-price elasticities, both Hicksian and Marshallian, possessed theoretically correct signs.

According to the autoregressive error model, electricity, gas and other fuels tend to be net substitutes (the Hicksian cross-price elasticities are positive and significant in two-thirds of the cases) but gross complements (the Marshallian cross-price elasticities are largely negative). The analysis based on national-level quarterly data, in contrast, found significant substitution possibilities, net and gross, between electricity and residual fuels and between gas and residual fuels. However, contrary to expectations, the regression results suggested that Australian households consumed electricity and gas in a complementary fashion. The panel data-based analysis, on the other hand, found significant substitution possibilities between gas and other fuels only. The cross-price elasticities between electricity and gas were positive but not significant.

Failure to find theoretically correct signs of some of the inter-fuel substitution elasticities, especially in the case of panel data where 280 observations were employed, appears to be largely attributable to insufficient price variation. During the past 14 years, relative fuel prices have had little variation and real fuel prices have generally declined. In fact, variations in household energy demand during this period, are primarily explained by the state-specific factors and temperature variations. Prices and income have played a very minor role. Fuel prices, especially that of residual fuel, changed markedly during the late 1970s and early 1980s but the electricity/gas price ratio remained quite stable which, in combination with the gas supply constraints, most probably resulted in the wrong signs for the national-level, quarterly data-based cross-price elasticities between electricity and gas. However, before drawing any conclusions, it seems appropriate to test the robustness of elasticity estimates using different functional specifications. This question is the subject matter of the next chapter.

Notes

[1] Considerable attention has, however, been paid to study the demand for energy at the level of specific end-uses, such as cooking, cooling, space heating, and water heating (Goldschmidt 1988; Bartels and Fiebig 1990; Fiebig *et al.* 1991; Bauwens *et al.* 1994; Bartels *et al.* 1996a; and Bartels and Fiebig 2000).

[2] The states considered in this analysis are New South Wales, Victoria, Queensland, South Australia, and Western Australia. The Northern Territory, Tasmania and the Australian Capital Territory are not included due to data limitations. Data was obtained for these three regions but it could not be included in the analysis as most of the observations were zero due to the fact that figures were rounded off to the nearest million dollars.

[3] The inclusion of a trend variable to capture the impact of changing technology is common in factor demand studies using time-series data, see, for example, Berndt and Wood (1975) and Turnovsky *et al.* (1982).

[4] While the linear approximation greatly simplifies the econometric implementation of the model, it is not however without a cost. The estimates of demand elasticities based on the linear approximate system, for instance, are different from those obtained using the nonlinear AI model (Green and Alston 1990; Alston *et al.* 1994). Furthermore, conventional symmetry restrictions ($\gamma_{ij} = \gamma_{ji}$) do not in general make the system symmetric, requiring additional symmetry restrictions (Chen 1998:311).

[5] The system is singular in the sense that the sum of the expenditure shares at each point in time equals one of the regressors, the unit variable.

[6] For details, see Berndt and Savin (1975:942-7).

[7] Moschini *et al.* (1994:61) note that weak separability is a commonly invoked assumption in the analysis of meat demand. Chalfant (1987), for example, employed this assumption while modelling the demand for beef, veal, pork, fish and poultry for the United States. It is also a generally employed assumption in the estimation of electricity demand functions by time of use, see Filippini (1995).

[8] For some other applications based on the logit model, see Tyrrell and Mount (1987), Considine (1989a,b), Jones (1995) and Dumagan and Mount (1996).

[9] Dynamic translating and scaling are two specifications which introduce parameter variation in empirical demand studies in a systematic way. The two procedures are fairly general and can be used with any demand system provided the system can be derived from well-behaved preferences. A subset of parameters is singled out with a view to relating it to past consumption. In the context of a Linear Expenditure System (LES), for instance, it is a common practice to introduce parameter variation by relating minimum consumption requirements of various goods to their past consumption levels. For further details, see Pollak and Wales (1992:102-12).

[10] For some other applications of this method, see Anderson and Blundell (1983, 1984) and Anderson (1991).

[11] As mentioned above, this linear approximate AI/VECM methodology is applied to national-level quarterly data for the period third quarter 1969 to second quarter 1998, giving a total of 116 data points.

[12] It has almost become a standard practice to treat predicted expenditure shares as fixed while computing the standard errors of the elasticity estimates, see, for example, Chalfant (1987).

[13] The expenditure on natural gas as a per cent of total energy expenditure rose from a little less than 14 per cent in the early 1980s to around 18 per cent in 1997.

[14] The non-energy price index is, in fact, the consumer price index.

[15] For a proof, see Kmenta and Gilbert (1968) and Dhrymes (1973).

[16] The generalised R^2 is due to Berndt (1991:469-70).

[17] In Chapter 5, which – using the estimated consumer energy demand structure and, more precisely, the elements of the Slutsky substitution matrix – attempts to estimate the deadweight loss of a carbon tax, (local) curvature restrictions are imposed to ensure the quasi-concavity of the underlying expenditure function at the point of the restrictions.

[18] The fact that the other fuels equation is dropped for the purposes of estimation implies that the estimates of $Cov(\gamma_{13},\beta_1)$, $Cov(\gamma_{13},\beta_3)$, $Cov(\gamma_{23},\beta_2)$, $Cov(\gamma_{23},\beta_3)$ and $Cov(\gamma_{33},\beta_3)$ and hence the corresponding estimates of the standard errors of price elasticities are not obtained. This problem is overcome by estimating once the electricity and fuel equations and then gas and fuel equations.

[19] In the static model in which each and every element of the R matrix is assumed to be equal to zero. DW, in this static model, was less than unity in all cases but the null of stationary residuals was not rejected in each case.

[20] For evidence, see Rothman *et al.* (1994).

[21] However, in a recent study Weng and Mount (1997) found the demand for electricity, gas and oil by the US residential sector to be price inelastic.

[22] See, for instance, Donnelly (1984) and Hawkins (1975).

[23] See, for instance, Donnelly (1984) for some estimates.

[24] The sign of this coefficient, for example, remained negative when the separability assumption was invoked to reduce the number of parameters.

[25] In 1997, 43.3 per cent of Australian homes were connected to the gas grids (AGA 1998).

[26] An attempt was made to account for this factor by introducing the fraction of households connected to gas reticulation systems as another explanatory variable. It was, however, dropped later due to its insignificance.

Appendix Table A3.1 **Regression results, annual data**

Variables	Parameter value	Standard error	Approximate t-score
α_1	1.4911*	0.3775	(4.97)
α_2	0.3882	0.2167	(0.81)
α_3	-1.0517*	0.3145	(3.34)
γ_{11}	0.1301*	0.0347	(3.23)
γ_{12}	-0.0758**	0.0222	(2.66)
γ_{13}	-0.0543**	0.0213	(2.56)
γ_{22}	0.0659*	0.0176	(3.74)
γ_{23}	0.0099	0.0093	(1.07)
γ_{33}	0.0444**	0.0171	(2.59)
β_1	-0.1331**	0.0605	(2.20)
β_2	-0.0543	0.0379	(1.43)
β_3	0.1875*	0.0501	(3.74)
λ_1	0.0009	0.0021	(0.43)
λ_2	0.0034*	0.0007	(4.59)
λ_3	-0.0043*	0.0015	(2.87)
$\bar{r}_{11}$	0.5968*	0.1342	(4.45)
$\bar{r}_{12}$	-0.9518*	0.3277	(2.90)
$\bar{r}_{21}$	-0.0453	0.0716	(0.63)
$\bar{r}_{22}$	0.5948*	0.2189	(2.72)
$\tilde{R}^2$	0.999995		

Notes: 1- $DW_1 = 2.37$, $DW_2 = 2.33$, $DW_3 = 2.21$, $R^2_1 = 0.946$, $R^2_2 = 0.947$, $R^2_3 = 0.971$. 2. *-significant at the 1 per cent level, ** significant at the 5 per cent level, *** significant at the 10 per cent level.
Source: Author's estimations.

Appendix Table A3.2 **Regression results, quarterly data**

Variables	Dynamic model		Static model	
	Value	T-score	Value	T-score
α_1	0.0445*	(5.40)	0.0385*	(11.59)
α_2	0.0069	(0.61)	-0.0084*	(4.12)
α_3	0.0046	(0.28)	0.0181*	(6.05)
α_4	0.9440*	(76.98)	0.9517*	(245.30)
γ_{11}	0.0057*	(3.70)	0.0062*	(7.47)
γ_{12}	-0.0030*	(3.25)	-0.0009***	(1.87)
γ_{13}	0.0028*	(3.58)	0.0031*	(10.21)
γ_{14}	-0.0055*	(3.70)	-0.0083*	(9.94)
γ_{22}	0.0014	(1.04)	0.0035*	(4.79)
γ_{23}	0.0024**	(2.51)	0.0006**	(2.40)
γ_{24}	-0.0008	(0.55)	-0.0032*	(4.82)
γ_{33}	-0.0031**	(2.28)	-0.0006**	(2.46)
γ_{34}	-0.0021**	(2.15)	-0.0030*	(8.63)
γ_{44}	0.0084*	(4.07)	0.0145*	(13.95)
β_1	-0.0034*	(3.56)	-0.0026*	(6.78)
β_2	-0.0005	(0.43)	0.0013*	(5.63)
β_3	0.0000	(0.01)	-0.0017*	(4.93)
β_4	0.0039*	(2.82)	0.0030*	(6.67)
δ_{11}	0.0001	(0.37)	0.0001	(0.70)
δ_{12}	-0.0008**	(2.03)	-0.0005*	(5.27)
δ_{13}	-0.0001	(0.09)	-0.0004**	(2.53)
δ_{14}	0.0008***	(1.83)	0.0008*	(3.75)
δ_{21}	0.0004	(1.36)	0.0006*	(3.28)
δ_{22}	0.0007	(1.61)	0.0006*	(5.27)
δ_{23}	0.0010	(1.50)	0.0015*	(10.74)
δ_{24}	-0.0021*	(4.52)	-0.0026*	(12.74)
δ_{31}	0.0039*	(12.84)	0.0041*	(22.69)
δ_{32}	0.0027*	(5.52)	0.0020*	(18.49)
δ_{33}	0.0012	(1.58)	0.0020*	(13.73)
δ_{34}	-0.0077*	(15.85)	-0.0081*	(39.55)
Log L	2243.9280		2105.4760	

Note: *-Significant at the 1 per cent level, ** significant at the 5 per cent level, *** significant at the 10 per cent level.
Source: Author's estimates.

Appendix Table A3.3 **Regression results, panel data**

Parameters	Value	Standard error	T-score
α_1	0.0660	0.0087	(7.61)
α_2	-0.0325	0.0114	(2.85)
α_3	-0.0022	0.0031	(0.71)
α_4	0.9687*	0.0152	(63.54)
γ_{11}	0.0135*	0.0020	(6.81)
γ_{12}	0.0022	0.0017	(1.30)
γ_{13}	-0.0007	0.0005	(1.28)
γ_{14}	-0.0149*	0.0014	(10.54)
γ_{22}	-0.0001	0.0021	(0.04)
γ_{23}	0.0020*	0.0005	(3.73)
γ_{24}	-0.0041**	0.0020	(2.08)
γ_{33}	0.0012*	0.0003	(4.06)
γ_{34}	-0.0026*	0.0005	(4.75)
γ_{44}	0.0216*	0.0028	(7.76)
β_1	-0.0065*	0.0010	(6.29)
β_2	0.0042*	0.0014	(3.07)
β_3	0.0003	0.0004	(0.95)
β_4	0.0020	0.0018	(1.09)
Quarterly dummy variables			
δ_{11}	0.0003***	0.0002	(1.81)
δ_{12}	0.0004**	0.0002	(2.05)
δ_{13}	0.0033*	0.0002	(18.76)
δ_{21}	-0.0004	0.0003	(1.37)
δ_{22}	0.0007*	0.0003	(2.59)
δ_{23}	0.0024*	0.0002	(10.04)
δ_{31}	-0.0001***	0.0001	(1.92)
δ_{32}	0.0010*	0.0001	(14.03)
δ_{33}	0.0014*	0.0001	(20.41)
δ_{41}	0.0001	0.0003	(0.43)
δ_{42}	-0.0020*	0.0003	(6.05)
δ_{43}	-0.0071*	0.0003	(21.87)
State dummy variables			
S_{11}	0.0005**	0.0002	(2.09)
S_{12}	-0.0016*	0.0002	(6.78)
S_{13}	0.0007*	0.0002	(3.61)
S_{14}	0.0015*	0.0002	(7.80)
S_{21}	-0.0021*	0.0003	(6.78)

S_2	0.0050*	0.0003	(16.52)
S_{23}	-0.0024*	0.0003	(8.90)
S_{24}	0.0013*	0.0003	(4.66)
S_{31}	-0.0006*	0.0001	(7.47)
S_{32}	0.0009*	0.0001	(10.79)
S_{33}	-0.0007*	0.0001	(9.38)
S_{34}	0.0008*	0.0001	(10.20)
S_{41}	0.0022*	0.0004	(5.17)
S_{42}	-0.0044*	0.0004	(10.51)
S_{43}	0.0024*	0.0004	(6.61)
S_{44}	-0.0035*	0.0004	(9.82)
Log L	4910.089		

Notes: $DW_1 = 2.07$, $DW_2 = 1.95$, $DW_3 = 1.97$, $DW_4 = 1.94$ $R^2_1 = 0.85$, $R^2_2 = 0.84$, $R^2_3 = 0.88$, $R^2_3 = 0.87$. *-Significant at the 1 per cent level, ** significant at the 5 per cent level, *** significant at the 10 per cent level.
Source: Author's estimations.

4

The impact of a carbon tax on consumer energy demand and CO_2 emissions

Synopsis

Using the dynamic OLS (DOLS) framework developed by Stock and Watson (1993) and national-level quarterly data, this chapter reports estimates of the equilibrium elasticities of the consumer demand for electricity, gas and other fuels. The demand for a fuel in this equilibrium or long-term relationship is assumed to depend on the own-price of the fuel, prices of the two other fuels, per capita real income and the weather. The parameters characterising the equilibrium relations are generally estimated with a desirable degree of precision. Significant substitution possibilities are found between electricity and gas and between electricity and other fuels. However, the cross-price elasticity of gas with respect to the price of residual fuels is negative.

The demand elasticities are used to project residential energy demand and associated CO_2 emissions over 2000 to 2010, under two sets of assumptions. In the baseline case, it is assumed that the independent variables will grow at the trend growth rate of the last 10 years. In the other scenario, residential energy demand and CO_2 emissions are projected assuming that a tax of $300, in 1998 dollars, per tonne of carbon is in place. For the sake of comparison, two other estimates of energy demand elasticities, which are estimated in Chapter 3, are also employed. Total (residential) energy demand and CO_2 emissions are projected to grow at a rate of 1-1.4 per cent per annum in the baseline case. The carbon tax, which is assumed to be applied in a gradual fashion, is expected to reduce this rate to around 0.6 per cent.

4.1 Introduction

There are two main objectives of this chapter. The first is to estimate the consumer energy demand structure, including electricity, gas and other fuels – a task assigned in the previous chapter with a view to obtaining a second opinion on inter-fuel relationships, especially between electricity and gas. Single-equation techniques, which are not very attractive for obvious reasons, are chosen in this respect as they offer more flexibility in the treatment of dynamics. More precisely, this chapter uses the dynamic OLS developed by Stock and Watson (1993) to estimate separately the consumer demand for electricity, gas and residual fuels. The study, in this respect, employs national-level quarterly data for the period from the third quarter 1969 to the second quarter 1998.

The second objective of this research is to project residential energy and associated CO_2 emissions over the period 2000 to 2010 using the estimated energy demand structure in this chapter and in the previous one. Both energy demand and CO_2 emissions are projected first, assuming that the independent variables – fuel prices, average consumer price level and household income – follow the trend of the last 10 years. In an alternative scenario, residential energy demand and emissions are projected assuming that a carbon tax is imposed on fuel consumption depending on the content of CO_2 of individual fuels.

The rest of the chapter is organised as follows. The methodology is explained in Section 4.2. A brief description of the data and its sources can be found in the next section. Results of time-series analysis of the variables involved in this study are presented in Section 4.4. Regression results are reported and discussed in Section 4.5. In Section 4.6 projections of residential energy demand and CO_2 emissions are reported and analysed. Finally, the study is summarised and some concluding remarks are made in Section 4.7.

4.2 Methodology

4.2.1 Econometric model

As mentioned above, this chapter follows a single equation approach to modelling the demand for electricity, gas and the other fuels for domestic cooking, cooling, heating and lighting purposes. It is postulated that the demand for the ith fuel depends on the price of the ith fuel, prices of substitute fuels, prices of complementary goods and income. Energy consumption is also greatly influenced by temperature. The demand for space heating, for instance, is high during winter and almost non-existent during summer. Similarly, the demand for electricity on account of cooling purposes goes up on a hot day. The significance of this factor becomes very prominent in this case because this study employs quarterly data to estimate energy demand.

Temperature is typically represented in energy consumption models by two climate variables: cooling degree-days (CDD) and heating degree-days (HDD). For a national level study that uses aggregate data, country level measures of CDD and HDD are needed. A potential problem with these aggregate or average estimates is that a substantial amount of information is lost during the process of aggregation or averaging. Indeed, national-level measures of CDD and HDD were constructed but dropped from the regression analysis because of the insignificance of the regression coefficients. Therefore, this study uses quarterly dummy variables to reflect the impact of temperature on energy consumption. Assuming a log-linear functional specification, the long run or equilibrium demand relationship for the ith fuel is, therefore:

$$\log(q_{it}) = \alpha_{0i} + \sum_{j=1}^{j=3} \alpha_{ij} \log(p_{jt}) + \beta_i \log(y_t) + \sum_{q=1}^{q=3} \delta_{iq} d_q + u_{it} \tag{4-1}$$

where

q_{it}	per capita real consumption in average 1990 dollars of the ith fuel;
p_{it}	price index of the ith fuel relative to the consumer price index;
y_t	per capita real household consumption expenditure in average 1990 dollars;
d_1	a dummy variable that takes a value of one in the first quarter and a value of zero during the other three quarters;
d_2	a dummy variable that takes a value of one in the second quarter and a value of zero during the other three quarters;
d_3	a dummy variable that takes a value of one in the third quarter and a value of zero during the other three quarters; and
u_{it}	Stochastic error term, which is assumed to satisfy the usual assumptions of OLS.

It has become popular among applied economists and particularly among time-series econometricians to consider the equilibrium or long-term relationship as the cointegrating relationship among the variables of a model (Stock and Watson 1993; Masih and Masih 1996). A significant body of literature has emerged which focuses on evolving estimators of cointegrating vectors. This study employs the dynamic OLS method developed by Stock and Watson (1993) with a view to estimating the parameters characterising the long-term demand for the three fuels. DOLS, as opposed to many other estimators, does not require that the individual series in a long-term relationship be integrated of order one, that is, I(1), as it is also applicable to systems involving variables of differing, higher orders of integration (Stock and Watson 1993:783-4). In the case of I(1) series, this technique involves regressing one variable on the contemporaneous levels of the other variables and on the leads and lags of their first differences and a constant term.

The presence of some simultaneous equation bias can be expected. As do most researchers, the average as opposed to the marginal prices of the different fuels is used. The existence of multi-part tariffs and different tariff structures in different regions of the country at a given point in time implies that prices, in turn, are expected to be influenced by the corresponding fuel quantities. As Stock and Watson (1993) have shown, the presence of lead and lag values of the differenced variables in the estimating equation of a cointegrating vector deals with this simultaneity bias along with small sample bias. Assuming that the individual variables of the model are all I(1), the estimating equation of DOLS can be written as:

$$\log(q_{it}) = \alpha_{0i} + \sum_{j=1}^{j=3} \alpha_{ij} \log(p_{jt}) + \beta_i \log(y_t) + \sum_{q=1}^{q=3} \delta_{iq} d_q + \sum_{j=1}^{j=3} \sum_{k=-K}^{k=K} \eta_{jk} \Delta \log(p_{jt-k}) + \sum_{k=-K}^{k=K} \lambda_k \Delta \log(y_{t-k}) + \varepsilon_{it} \tag{4-2}$$

The above equation is estimated for each of the three fuels using OLS. The value of K, as is apparent from Equation (4-2), is taken to be a constant in each equation, which is determined using the Wald test procedure. However, the number of lead and lag variables, K, is allowed to vary across fuels.

4.2.2 Projection method

With a view to projecting residential energy demand a simple procedure is used. The (constant) growth rates of demand for individual fuels are obtained as:

$$g_i = \sum_{j=1}^{3} \varepsilon_{ij} \pi_j + \varepsilon_{i,cpi} \pi_{cpi} + \eta_{i,y} g_y, \qquad i = 1,2,3 \tag{4-3}$$

where g stands for growth rate; π = inflation rate (π_1, for instance, stands for electricity price inflation); y = per capita income, CPI = average consumer price level; and ε and η stand for elasticity. The growth rate of a fuel, according to this specification, is a weighted average of the inflation rates of the three fuels, the average inflation rate and the per capita income growth rate, where the weights are the corresponding Marshallian elasticities. The growth rate of total fuel demand, as opposed to the growth rate of per capita fuel demand, is obtained by adding the population growth rate to the corresponding per capita growth rate of a fuel. These rates are applied to the actual 1998-fuel consumption data to obtain the projected fuel demand series.

In the case of the baseline scenario or the business-as-usual scenario, it is assumed that the independent variables will grow over the projection period at the trend rate of the last ten years, 1989 to 1998. The other scenario, that is, the carbon tax scenario, assumes that a tax of $300 per tonne of carbon, in 1998 dollars, is applied and that the revenue collected is recycled in the form of a payroll tax reduction.[1] The assumption of a recycled carbon tax is invoked for the sake of convenience as the empirical evidence on the subject suggests that an economy-wide carbon tax may leave income and general prices largely unchanged if the tax revenue is recycled in the form of a payroll tax reduction (Common and Hamilton 1996; McDougall and Dixon 1996). Indeed, GDP is estimated to expand slightly and prices increase, according to Common and Hamilton's (1996) and McDougall and Dixon's (1996) estimations; however, for the sake of convenience such favourable impacts are ignored. In this respect it is also supposed that the tax will be applied gradually such that fuel prices will reflect the full amount of tax in 2010, while fuel prices will increase at a constant proportionate rate.

The CO_2 emissions from each fuel, in turn, are computed as:

$$E_i = O_i \times \theta_i \times q_i \qquad (4\text{-}4)$$

where E_i stands for CO_2 emissions from combustion of the ith fuel; θ_i is the CO_2 emission factor of the ith fuel (in giga grams of CO_2 per peta joule of the fuel under consideration); and O_i is the oxidation factor of the ith fuel. The case of the electricity emission factor needs some elaboration as electricity consumption itself is not carbon emitting. Rather, there is CO_2 emission at the generation stage. With a view to obtaining a CO_2 factor for electricity, the CO_2 emissions associated with the power generation sector are divided by total electricity generated. Power production and CO_2 data for the period 1990 to 1997 were used to derive an average CO_2 factor for the fuel.[2]

For the sake of comparison, two other estimates of demand elasticities, in addition to those of the DOLS, are used to project consumer energy demand and CO_2 emissions. In one set of the estimates, the Almost Ideal (AI) demand system is parameterised as a vector error correction model (VECM), which is estimated using the same data, that is, the data set that is employed to estimate the DOLS model. The other set of demand elasticities is obtained by applying the static AI (S-AI) model to a panel data consisting of five states. The demand system in these cases is closed by treating all other household expenditure as a fourth demand variable.

4.3 Data and estimation

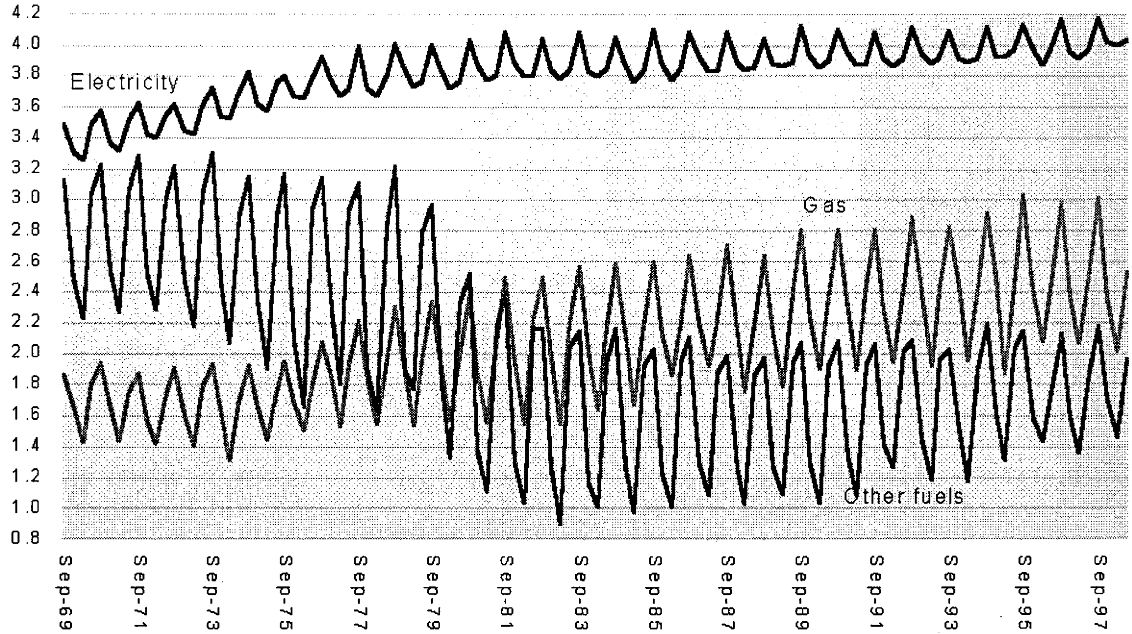
The data used in this analysis, obtained from the Australian Bureau of Statistics (ABS), are quarterly (seasonally unadjusted) spanning the period from the third quarter 1969 to the second quarter 1998, that is, 116 data points. Data for total household consumption expenditure, household expenditure on energy, and the population were obtained from various issues of the 'Australian National Accounts: National Income, Expenditure and Product' (ABS Catalogue No. 5206.0). Both nominal and constant values of expenditure, at average 1990 prices, were obtained. The break-up of the energy category into expenditures on electricity, gas and other fuels was also obtained from the Bureau on request, as these data are not published.

This study used average as opposed to marginal prices in the regression analysis. The price deflators were constructed by dividing the nominal variables by the corresponding real ones. Marginal prices, which are appropriate from the viewpoint of economic theory, were not considered due partly to data limitations and, more importantly, due to the complications associated with the existence of multi-part tariffs and different tariff structures in different regions at a given point in time. The quantity data on different fuels was taken largely from 'Australian Energy: Market Developments and Projections to 2014-15' published by the Australian Bureau of Agricultural and Resource Economics (Bush *et al.*, 1999). All estimation was carried out in SHAZAM Version 8.

4.4 Time-series analysis

Real per capita expenditure on electricity, gas and the residual fuels is plotted in Figure 4.1 and the corresponding price (real) time-paths are presented in the next figure. A seasonal pattern in energy consumption is apparent from the energy consumption plots. Electricity consumption, for instance, is highest during the third quarter, the coldest quarter. It falls sharply during the next quarter and to a lower level during the first quarter. This pattern of seasonal variations indicates clearly that Australian households consume a lot more electricity during winter than in summer. This is not surprising because summer is relatively short and mild in the regions where most of the population resides. The demand for space cooling and thus electricity is not very high as a result. Winter, by contrast, is long and requires significant amounts of space and water heating.[3] Gas and residual fuels consumption is characterised by more or less the same kind of seasonal patterns.

Figure 4.1 **Quarterly real energy expenditure by fuel type** (log)

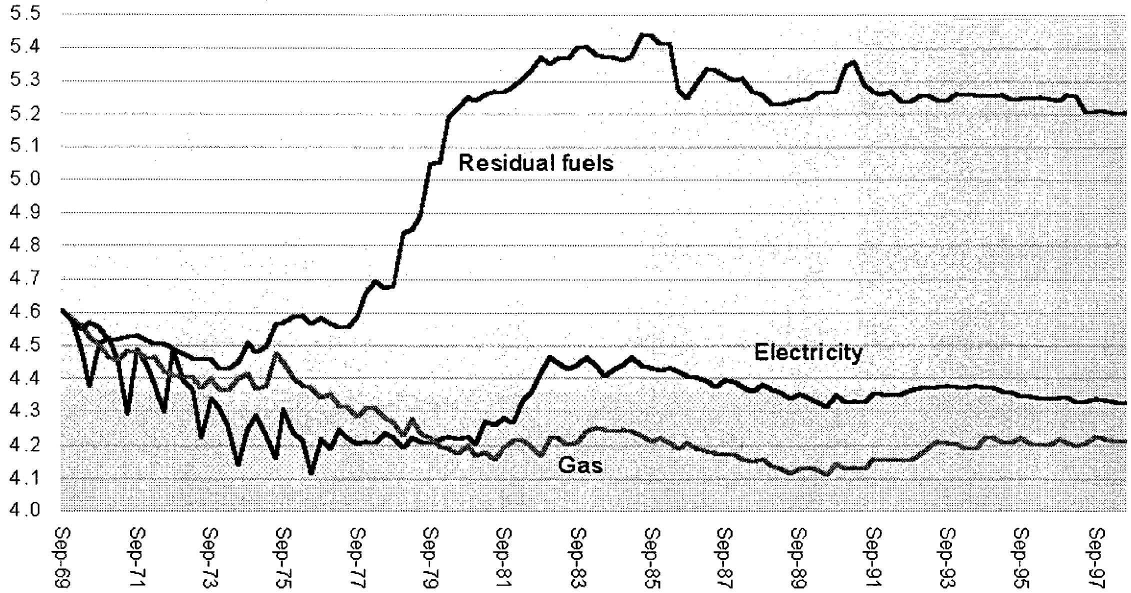


Sources: Australian Bureau of Statistics, 1999. *Australian National Accounts: national income, expenditure and product*, Catalogue No. 5206.0, Canberra; author's calculations.

A cursory look at the figure shows that electricity and gas consumption rose and that of miscellaneous fuels fell in a fluctuating fashion during the past three decades. A closer look at the figure, however, reveals another behaviour which is consistent across three variables. The second oil price shock, which hit the Australian economy during the third quarter of 1978, permanently changed the pattern of fuel consumption. The shock, for example, slowed the growth rate of electricity consumption and increased the slope of the trend in gas consumption. In the case of the residual fuels, it seems that the major supply-side event permanently lowered the level without greatly altering the slope of the trend (in order to see the impact of the oil shock more clearly, see Appendix Figures A4.1 to A4.6).

Seasonal patterns are not obvious in the price graphs. This might be expected as seasonal variations in energy demand, especially those of electricity and gas, are not managed through price changes to any significant extent. It is, however, clear that the oil shock of 1978 also altered the price paths. The event reversed the sharp downward trend in the real electricity price, at least for the time being. The index has been falling since the early 1980s but at a mild pace. The gas price, in contrast, has become more or less stable after settling down from the shock, while it too was declining during the early 1970s.

Figure 4.2 **Quarterly real price indices** (log)



Sources: Australian Bureau of Statistics, 1999. *Australian National Accounts: national income, expenditure and product*, Catalogue No. 5206.0, Canberra; author's calculations.

The price of residual fuels rose very sharply during the late 1970s and early 1980s in response to the shock. It moved to a downward trend after settling down from the shock. It seems that the oil shock of 1973 also influenced the price of miscellaneous fuels. The impact is, however, very minor relative to that of the second shock.

The presence of a structural break in the series suggests that the standard type of Dickey-Fuller and Phillips-Perron procedures would be biased towards the null hypothesis of non-stationarity. Perron (1989) has shown that the standard type of unit root testing procedures significantly lose power to reject the null hypothesis of a unit root against the alternative hypothesis of a trend stationary process if the underlying data generating process is trend stationary with a structural break. Perron (1989), in this regard, using the famous Nelson and Plosser (1982) data and accounting for the structural break in 14 US macro variables associated with the Great Depression, rejected the null hypothesis of a unit root in 11 out of 14 variables which were found to be non-stationary by the Nelson and Plosser (1982) study.

For the purposes of this study it is assumed that the oil shock of 1978 changed not only the level but also the slope of the underlying trend function. Under the null hypothesis of a unit root the data generating process is represented as:

$$Y_t = a_1 + Y_{t-1} + (a_2 - a_1)DL + a_3DP + \xi_t \tag{4-5}$$

where $DP = 1$ if t = fourth quarter 1978 and zero otherwise; $DL = 1$ if t ≥ fourth quarter 1978 and zero otherwise; *as* are parameters and ξ_t is the error term. Under the alternative representation of a trend stationary process with a one-time break in the level and slope, the equation is

$$Y_t = a_1 + (a_2 - a_1)DL + a_4 t + (a_5 - a_4)DT + \xi_t \tag{4-6}$$

where t stands for the trend function; $DT = t\text{-}\tau$ for $t > \tau$ and zero otherwise and $\tau = 37$ – the observation which corresponds to the third quarter of 1978.

One way to implement this procedure is to estimate the alternative formulation first, Equation (4-6), and then apply the standard Dickey-Fuller procedure to the residuals obtained from this stage. This two-step procedure, however, implicitly assumes that the oil shock influenced the economy instantaneously. This is an assumption which does not hold in general and definitely not in this case as is apparent from Figures 4.1 and 4.2. In order to avoid this potential problem, Perron (1989) is followed and the following specification is used:

$$\begin{aligned} Y_t &= b_0 + b_1 Y_{t-1} + b_2 t + b_3 DT + b_4 DL + b_5 DP \\ &\quad + \sum_{q=1}^{q=3} c_q d_q + \sum_{i=0}^{m} f_i \Delta Y_{t-i} + \zeta_t \end{aligned} \tag{4-7}$$

where d_q is a dummy variable for quarter q as defined previously and ζ_t is an error term, which, it is assumed, satisfies the basic assumptions of OLS.

Lags of the first differenced variable are introduced to allow for the likely serial correlation problem. A fairly liberal procedure is adopted to choose the value of m. Lag length for a cointegrating equation is chosen to be m if the t-score associated with f_m is larger (in absolute terms) than 1.6 and all subsequent *ms* have a t-ratio of less than 1.6.[4] A maximum of 12 lags is considered. Three quarterly dummies are introduced in the above unit root equation due to the fact that quarterly data are used. The dichotomous variables are however, not included in the case of price variables because of the insignificance of the dummy coefficients in the corresponding unit root testing equation(s).

Perron (1989) shows that the critical values of the t-statistic depend upon the proportion of the sample prior to the structural break. This proportion happens to be roughly equal to 1/3 of the sample size. The critical value at the 5 per cent significance level, which is sourced from Perron (1989), is -4.17. The null hypothesis of a unit root is rejected if the absolute value of the t-score associated with b_1 is larger than 4.17.

The first two columns of Table 4.1 present unit root statistics from the application of Equation (4-7) to the variables included in this study. Clearly the null of non-stationarity is rejected only in the case of p_3 as the absolute value of the t-statistic is greater than the corresponding 5 per cent critical value. The last two columns report the standard type of Dickey-Fuller procedure performed on first differenced variables. Here, the null of a unit root is rejected easily at the 95 per cent level of confidence in each case. It is, therefore, concluded that all variables are I(1), except for the price of residual fuels, which is I(0).

Table 4.1 **Unit root test results**

Variables	Variables in level form		First differenced variables	
	Lags	t_α	Lags	t_α
p_1	12	-2.87	3	-4.23*
p_2	4	-2.91	3	-5.17*
p_3	0	-6.42*	2	-4.25*
y	4	-2.80	3	-4.44*
q_1	12	-2.43	3	-7.86*
q_2	3	-2.35	2	-27.80*
q_3	7	-3.38	4	-4.17*

Note: *- Significant at the 5 per cent level.
Source: Author's estimations.

The *trace* and the λ_{max} test statistics are reported in Table 4.2 for the three energy demand equations.[5] The case of electricity is considered first. Here, the null of no cointegrating vector against the alternative hypotheses is rejected by both test statistics at the 5 per cent level. In order to determine the number of cointegrating vectors the remaining hypotheses need to be tested. The null of $r \leq 1$ is not rejected against the alternative of $r > 1$ (or $r+1$). The same is true with respect to the remaining H_0s. It is, therefore, concluded that a unique cointegration vector characterises the postulated electricity demand relation.

The case of gas is considered next. Here, the null of no long-term relationship against the general alternative hypothesis is rejected using the trace test procedure with a probability value of nearly 5 per cent, as the corresponding 5 per cent critical value is 69.977. The hypothesis of $r = 0$ versus $r = 1$, by contrast, is rejected at almost the 10 per cent significance level with the help of the maximum eigenvalue procedure (10 per cent critical value, 30.818). All the subsequent nulls are not rejected even at the 20 per cent level of significance. Therefore, it is concluded that there exists a long-term relationship in the case of gas as postulated in (4-1) and that the relationship happens to be unique. Finally, the maintained hypothesis of no cointegration in the residual fuels case is rejected with overwhelming support from the data. There is, at the same time, no sensible way to reject the remaining nulls. This, again, leads to the same conclusion of a unique cointegration vector, this time in the case of the residual fuels.

Table 4.2 **Multiple unit root test results**

H_0	Electricity		Gas		Residual fuels	
	Trace	λ_{max}	Trace	λ_{max}	Trace	λ_{max}
$r = 0$	74.285**	33.953**	69.717***	30.553	78.020*	42.967*
$r \leq 1$	40.332	17.903	39.163	20.868	35.053	18.890
$r \leq 2$	22.429	11.810	18.295	14.205	16.163	8.286
$r \leq 3$	10.619	10.583	4.090	3.991	7.877	7.257
$r \leq 4$	0.036	0.036	0.099	0.099	0.620	0.620

Notes: 1. The alternative hypothesis is a general one in the case of the trace test but r+1 in the case of the λ_{max} test. 2. Critical values are taken from Johansen and Juselius (1990): A single asterisk (*) indicates significance of the respective coefficient at the 1 per cent level; a double asterisk (**) indicates significance at the 5 per cent level; and, finally, a triple asterisk (***) reflects the rejection of the null hypothesis at the 90 per cent level of confidence.

Source: Author's estimations.

4.5 Regression results

The estimates of long-run demand elasticities and the estimated coefficients of quarterly dummy variables are reported in Table 4.3 along with the t-ratios and values of the adjusted R-square. The coefficients, and hence t-scores, of the lead and lag variables are not presented, primarily because individual (lead and lag) parameters lack economic interpretation of any significance (a complete set of parameters is given in the Appendix Tables A4.1 to A4.3). The electricity and the residual fuel demand functions are estimated with j = +/- *5* and, therefore, 20 additional variables. The gas demand function, in contrast, includes two leads and lags. The choice with regard to the number of lags is made using a Wald test, that is, an extra lead and lag set is taken as part of the dynamic equation if the null hypothesis of all coefficients belonging to the set being jointly equal to zero is rejected. The adjusted R^2 is fairly high across the three regression equations. Variations in fuel use during the past 30 years or so, therefore, are mostly explained by fuel prices, per capita income, the weather proxied by quarterly dummy variables, and lead and lag variables of prices and income.

Table 4.3 **Regression results**

Variables	Electricity	Gas	Residual fuels
α	0.187	-9.497	-1.107
	(0.73)	(20.11)	(1.51)
p_1	-0.951*	0.870*	0.987*
	(12.39)	(7.17)	(3.01)
p_2	0.205*	-0.702*	1.295*
	(2.28)	(3.26)	(2.74)
p_3	0.377*	-0.186*	-1.168*
	(12.49)	(3.20)	(6.93)
y	0.523*	1.882*	0.538*
	(11.37)	(23.55)	(4.07)
d_1	-0.034	-0.348*	0.359
	(0.67)	(2.79)	(1.36)
d_2	0.124***	0.019	2.107*
	(1.91)	(0.21)	(5.40)
d_3	0.339*	0.438*	1.340*
	(4.72)	(4.06)	(3.64)
$\overline{R}^2$	0.981	0.964	0.971

Notes: 1. The standard errors are due to Newey and West (1987). 2 * significant at the 1 per cent level; ** significant at the 5 per cent level; *** significant at the 10 per cent level.
Source: Author's estimations.

The estimated intercept for electricity and miscellaneous fuel consumption is not significantly different between the first quarter and the fourth quarter. However, gas use is found to be markedly lower during the January-March period in relation to the base period as the respective dummy variable coefficients are negative and statistically significant. This is not unexpected because gas consumption for space heating is almost non-existent during the first quarter but some demand is expected during the base trimester, especially during the early part of the quarter.

Use of wood, heating oil and other miscellaneous fuels along with the consumption of electricity is estimated to be higher during the second quarter than in the previous two quarters. The finding with regard to electricity is, however, less sure as the relevant dummy variable coefficient is significant only at the 10 per cent level. Gas use, by contrast, is roughly similar between the second quarter and the base period. Demand for space heating is essentially the same between the two quarters because of relatively similar temperatures.

Finally, there is significant evidence that electricity, gas and miscellaneous fuels consumption increases very sharply during the third quarter, the coldest quarter. This is hardly surprising as the demand for space heating and hence fuel demand is highest during this quarter. Consumption of electricity and gas is expected to be highest during this quarter while that of the residual fuels is estimated to peak during the third quarter as the second quarter dummy coefficient is larger than that of the corresponding third quarter in the miscellaneous fuels demand equation. Quarter-wise averages of real per person expenditures of the three fuels are reported in Table 4.4. The figures in this table tell roughly the same story with regard to the energy consumption patterns across quarters with, however, some exceptions. This is not unexpected because simple averaging according to quarters does not take into account the impact of price and income information.

Table 4.4 **Real per capita energy expenditure by fuel type and quarter** (1990 dollars)

Fuels	Quarters			
	First	Second	Third	Fourth
Electricity	42.66	45.76	54.27	45.34
Gas	5.58	8.85	12.66	7.94
Residual fuels	4.68	11.37	14.42	6.27
Total residential	52.55	65.98	81.35	59.55

Source: Author's estimations.

It seems that the Australian residential sector is quite sensitive to price variations as far as the demand for energy is concerned. The own-price elasticity of the residual fuels, for example, is greater (in absolute terms) than unity and that of electricity is nearly unity. The estimate of the gas price elasticity is -0.70 but the null hypothesis of a unitary elastic demand is not rejected even at the 10 per cent level. The same is true with regard to the other two elasticities.

Contrary to some of the findings in Chapter 3, the two cross-price elasticities between gas and electricity are positive and highly significant, implying that the two fuels are strong (gross) substitutes. Gas demand is, in fact, found to be more responsive to electricity price variations than to gas price changes. This result is in line with expectations and is good news for policy makers who aim to control carbon emissions associated with energy use.

The demand for residual fuels is not only own-price elastic but also is very sensitive to changes in the prices of the two other fuels. The income sensitivity of residual fuels, by contrast, is very low. Obviously, the households that use these fuels consider them a necessary expenditure. These sensitivities help to explain why the per capita consumption of this fuel has declined during the past three decades or so. The real prices of the two competing fuels, electricity and gas, declined by 16 per cent and 24 per cent, respectively during the last 30 years. The own-price of the residual fuels, by contrast, increased by almost 100 per cent during the same period. As a result of these unfavourable price movements, the demand for residual fuels declined in absolute terms despite an impressive rise in per capita incomes.

There is, however, one significant problem with this set of results. Gas demand is estimated to decline with an increase in the price of the residual fuels, holding other factors constant – a finding that is contrary to theoretical expectations. It is generally believed that gas is a very close substitute for wood and heating oil in the area, at least, of space heating. It also is a generally held belief that the share of gas in residential energy use has been increasing, primarily at the expense of residual fuels (AGA 1992).

4.6 Projection results

The projected average annual growth rates of per person energy consumption of the different fuels for the period 1998 to 2010 corresponding to the "business-as-usual" and "carbon tax" scenarios are reported in Table 4.5. The (total) CO_2 emission rates are also presented in the lower half of the Table. Per capita household energy use in the baseline case is expected to grow at a rate of 0.22 per cent per annum, according to the DOLS estimates. The VECM coefficient estimates, in contrast, predict relatively stable per capita energy use during the next 13 years while the S-AI coefficients show a slight decline. Total residential sector energy demand is, therefore, expected to grow at a rate of 1-1.4 per cent per annum as population is assumed to grow by 1.15 per cent annually. According to Bush *et al.* (1999:45), the sector's energy demand is projected to grow at a rate of 0.7 per cent per annum. This growth differential is largely because Bush *et al.* (1999) assumed a population growth rate of around 0.9 per cent for the forecasts.

Table 4.5 **Residential sector energy consumption and associated CO_2 emission projections under alternative scenarios**

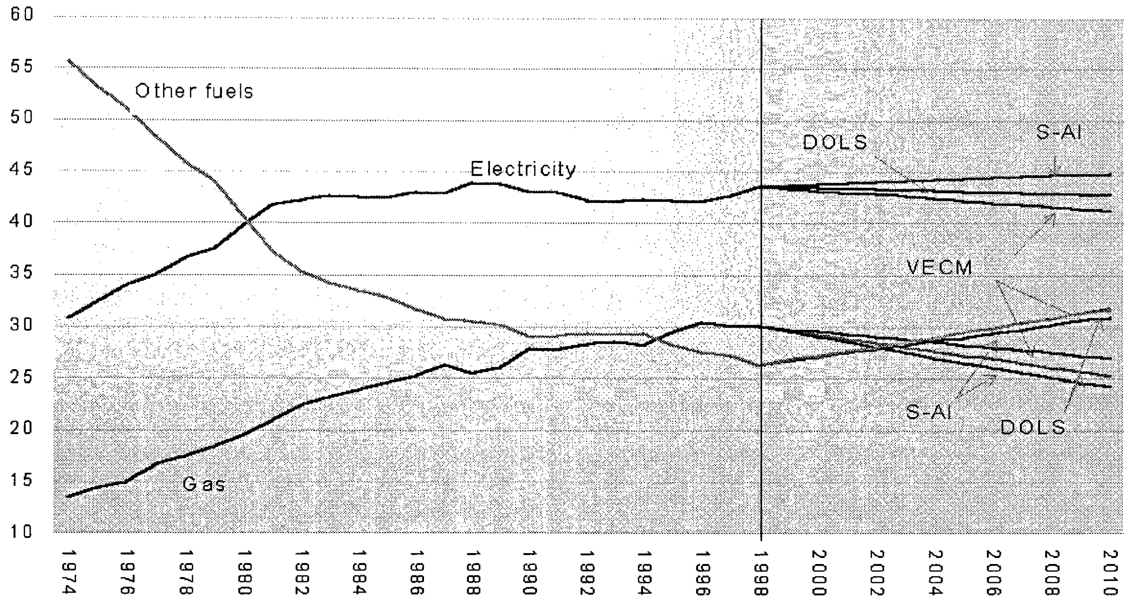
Fuels	Projected per person energy consumption growth rates					
	DOLS		VECM		S-AI	
	Baseline	Carbon tax	Baseline	Carbon tax	Baseline	Carbon tax
Electricity	0.06	-0.85	-0.41	-1.28	0.03	-0.90
Gas	-1.20	0.15	-0.85	-1.20	-2.03	1.78
Other fuels	1.82	0.15	1.61	-2.14	1.12	-1.01
Total	0.22	-0.27	0.05	-1.47	-0.22	-0.03
	Projected (total) CO_2 emissions rates					
Electricity	1.22	0.29	0.74	-0.14	1.18	0.24
Gas	-0.07	1.30	0.29	-0.06	-0.90	2.96
Other fuels	2.99	1.30	2.78	-1.01	2.28	0.13
Total	1.39	0.60	1.06	-0.27	1.14	0.61

Notes: Assumed inflation/growth rates
Baseline: electricity price = 2.27 per cent, gas price = 3.53 per cent, other fuel price = 1.93 per cent, CPI = 2.36 per cent, per capita income = 2.16 per cent, population = 1.15 per cent.
Carbon tax scenario: electricity price = 4.62 per cent, gas price = 3.60 per cent, other fuel price = 5.42 per cent, CPI = 2.36 per cent, per capita income = 2.16 per cent, population = 1.15 per cent.
Source: Author's estimations.

The projected growth rates of individual fuels are very different from the corresponding total energy use rates. In the case of the DOLS estimators, for instance, electricity demand is expected to remain more or less stable while the other two fuels are predicted to change markedly in the next 13 years. Demand for residual fuels, for example, is estimated to increase by 1.8 per cent annually, leading to an increase in its share in total energy use from one-quarter to nearly one-third by 2010 if prices and incomes follow the growth trend of the last 10 years (Figure 4.3). The two other estimators predict more or less the same pattern of variation in individual growth rates. Gas demand, for example, declines across the three estimators and residual fuel demand is projected to increase. This variation in energy use growth rates is primarily explained by the fact that, under this business-as-usual scenario, the real price of gas is rising while that of residual fuels is falling.

The residential sector CO_2 emissions in this scenario are estimated to grow at more than 1 per cent per annum. According to the DOLS estimators, for instance, total emissions are expected to increase from 49.5 million tonnes in the base-period, 1998, to 58.4 million tonnes in 2010, growing at an average annual rate of 1.4 per cent. The other two estimators show a relatively smaller proportionate increase in CO_2 emissions.

Figure 4.3 **Historical and projected (baseline) energy expenditure shares** (per cent)



Source: Author's estimations.

A tax of $300 per tonne of carbon on individual fuels leads to a reduction in per capita use of energy according to the DOLS and the VECM estimators. The DOLS estimators, for instance, predict a contraction in per person energy use at the rate of roughly 0.3 per cent per annum, whereas it predicted a slightly rising energy demand in the reference case. The contraction in domestic per person energy use, according to the VECM method, is quite significant, nearly 1.5 per cent per annum. The complementarity between electricity and gas and the high sensitivity of residual fuels to its own-price in the VECM version of the elasticities largely explains this result. The S-AI estimators, in contrast, predict a slight reduction in the rate of energy demand contraction despite the fact that the electricity and residual fuels demand is estimated to fall. Indeed, in this version of the results, the gas demand rate increases from -2 per cent in the baseline case to nearly 1.8 per cent in the alternative scenario which more than offsets the reduction in the use of the other two fuels.

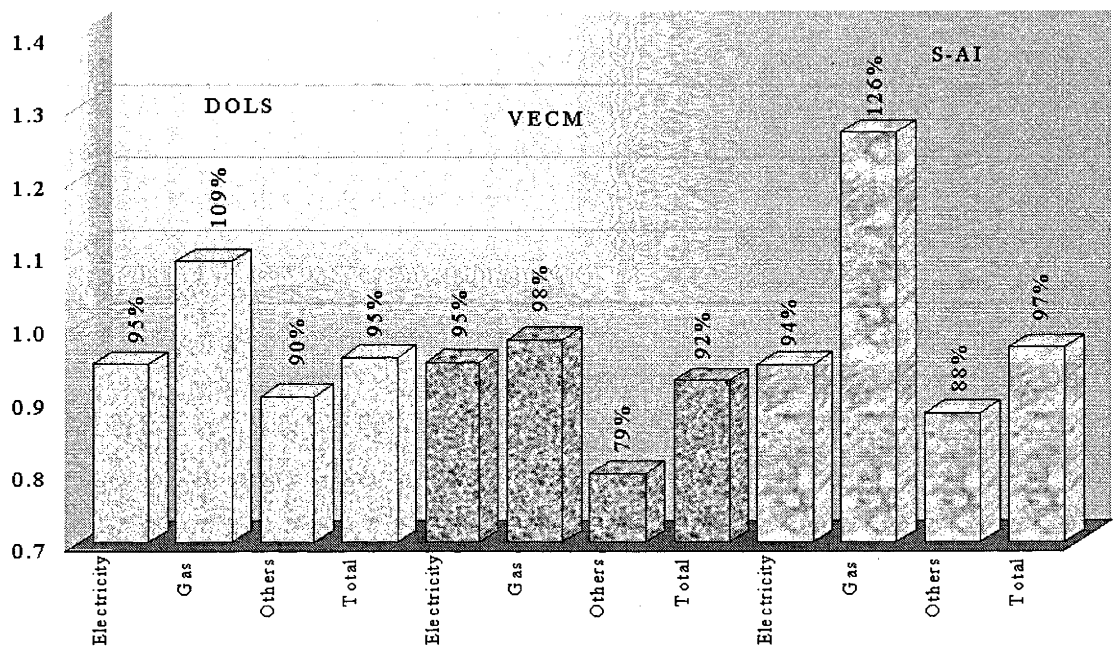
The growth rate of total CO_2 emissions falls by approximately one half in relation to the reference scenario in the case of the DOLS and the S-AI model. Interestingly, the two estimators predict the same growth rate of total emissions despite markedly different patterns across individual fuels. The VECM estimators, in contrast, predict falling CO_2 emissions, at a rate of around one-quarter of a percentage point. In the reference case of this model, total emissions were estimated to rise by 1 per cent annually. This marked change is largely due to a sharp fall in the growth rate of residual fuel related emissions, from 2.8 per cent in the reference case to -1 per cent in the alternative scenario. Indeed, according to the VECM estimators, the residual fuel demand is highly sensitive to own-price variations. Relatively high demand elasticity (own-price) coupled with relatively high fuel price inflation in the case of residual fuel category resulted in a sharp decline in its demand and thus emissions.

The S-AI estimator shows a significantly greater rise in gas demand under the carbon tax regime. In this case per person use of gas is predicted to increase from 6.2 MJ in 1998 to 7.6 MJ in 2010, growing at an average annual rate of nearly 1.8 per cent. The corresponding CO_2 emissions, according to this estimator, are expected to increase by more than 40 per cent between 1998 and 2010 due to a growth rate of nearly 3 per cent. The VECM estimators, by contrast, predict a significant reduction in per capita gas demand and roughly stable associated emissions, while the DOLS shows a modest growth of gas demand. This substantial variation in gas use growth rates across different estimators is primarily associated with cross-fuel price elasticity differentials. As mentioned previously, gas and electricity are complementary fuels in the VECM, and gas is highly sensitive to electricity price changes. The DOLS finds complementarity between gas and other fuels and thus suppresses gas demand growth owing to a 5.4 per cent rise in the price of residual fuels each year. It is only in the case of the S-AI model that gas is substitutable for electricity and other fuels and thus its demand rises rapidly due to a relatively greater increase in the prices of the other two fuels.

Figure 4.4 presents total (projected) CO_2 emissions between 1998 and 2010 under the alternative scenario as a percentage of the corresponding emissions under the baseline situation. Interestingly, the DOLS and the S-AI estimators project a roughly similar reduction in total emissions relative to the business-as-usual scenario, despite markedly different patterns across individual fuels. The S-AI model projects that the emissions accounted for by gas will increase by one quarter. The reduction in emissions in the case of the other two fuels more than offsets this rise and, as a consequence, total emissions are projected to decline by approximately 3 per cent. In the case of the DOLS procedure, gas related CO_2 emissions are projected to rise by 9 per cent while the electricity and residual fuels related emissions are estimated to fall, respectively, by 5 per cent and 10 per cent. On average, the DOLS estimators project a 5 per cent fall in total emissions in relation to the baseline emissions.

In the VECM version, the reduction in emissions relative to the business-as-usual scenario is greater than that predicted by the other two estimators. This result is partly attributable to the complementarity between electricity and gas, which reinforces the impact of the own-price increase rather than mitigating its impact through substitution as is happening in the other cases. Also, significantly more reduction in the other fuels CO_2 emissions derives from the fact that the VECM finds a highly sensitive (own-price) residual fuels demand.

Figure 4.4 **CO_2 ratios**



Source: Author's estimations.

Clearly, the residential sector's energy use and CO_2 emissions do not change much despite a substantial increase in fuel prices over a period of 13 years or so.[6] The DOLS and the S-AI model, indeed, predict increasing emissions relative to the base period, 1998. Similarly, the two estimators predict a reduction of 3-5 per cent in total CO_2 emissions between 1998 and 2010 relative to the total business-as-usual emissions for the same period. The VECM, however, shows a contraction in energy demand and CO_2 emissions but the wrong sign of the cross-price elasticities between electricity and gas distorts the results.

This finding of a sluggish response is partly because the relative fuel price change caused by a \$300 tax per tonne of carbon is only slight despite markedly different carbon coefficients across the three fuels. The CO_2 coefficient of electricity is 3.8 times higher than that of gas, but the electricity price per tonne of CO_2 is only 30 per cent lower than the corresponding gas price. Similarly, the CO_2 coefficient of electricity is

2.3 times larger than that of other fuels, but the electricity price per tonne of CO_2 is only 20 per cent higher, in CO_2 terms, than that of other fuels.

Further, and more importantly, the general consumer price level and the per capita income are assumed to be unaffected by the introduction of a carbon tax which implies the absence of the second round (negative) effects and hence no further reduction in energy demand and emissions. This is because, as discussed previously, carbon tax revenue is assumed to be recycled in the form of a payroll tax reduction. Empirical evidence on the subject suggests that an economy-wide carbon tax leaves income and general prices largely unchanged if the carbon tax revenue is appropriately recycled.

4.7 Conclusions

The residential energy demand in Australia was modelled and estimated in this chapter using single equation techniques. To this end, total domestic energy use was divided into the consumption of electricity, gas and a miscellaneous category, residual fuels. Long-run or equilibrium per person demand for a particular fuel was assumed to depend on the (own) price of that fuel, prices of the two other fuels, real per capita income and the state of the weather. The study used national-level quarterly data for the period from the third quarter 1969 to the second quarter 1998 – a total of 116 data points. The state of weather was represented by quarterly dummy variables.

Long-run parameters of the fuel demand relations were estimated using the Dynamic OLS framework suggested by Stock and Watson (1993). Dynamic OLS, which does not require that all variables be necessarily integrated of order one, has been shown to be robust to simultaneity and small sample bias. A prior examination of the variables detected the presence of a structural break in roughly all time-series that was associated with the oil shock of 1978. The unit root analysis, which took into account the shock, found all variables to be integrated of order one, except the price of the residual fuels which was found to be level stationary. Furthermore, the application of Johansen and Juselius procedures, the trace test and the maximum eigen value test, rejected the null hypotheses of no long-term relationship in each of three fuel demand equations.

Demand for the three energy categories was found to be fairly (own) price responsive as the null of unit elastic demand is not rejected in either case. The study found significant substitution possibilities between different categories of fuels. Interestingly, the demand for gas was found to be more sensitive to electricity price variations than to gas price changes. Also, electricity and residual fuels were found to be necessities whereas gas was a luxury. There is, however, one sticking point in this research. The cross elasticity of gas demand with respect to the residual fuel price was negative, although the cross-price elasticity of residual fuels demand with respect to gas price was positive and significant.

The estimates of energy demand elasticities were used to project consumer energy demand for individual fuels and associated CO_2 emissions under two scenarios. In the first case it was assumed that fuel prices, the average consumer price level, per capita income and population grow over the projection period, 2000 to 2010, at the trend rate of 1989 to 1998. The other scenario gradually imposed a tax per tonne of carbon on each fuel, increasing to \$300 per tonne of carbon in 2010. Meanwhile, fuel prices increase at a constant proportionate rate such that each price reflects the total amount of the tax in 2010. Income and the general price level in this alternative scenario were assumed to be unaffected under the assumption that the tax revenue thus collected is used to reduce payroll taxes.

In addition to the DOLS elasticities, this chapter considered two other sets of energy demand elasticities, estimated in the previous chapter, with a view to projecting energy demand and emissions. The first set of elasticities was obtained by expressing the Almost Ideal (AI) demand system as a vector error correction model (VECM) which is estimated using the same data. The other set was obtained by applying the static AI (S-AI) model to a panel data set comprising five states.

The estimated growth rate of total energy demand and emissions in the baseline case ranges between 1.06 per cent and 1.39 per cent. Significant disparities are found as far as growth rates of individual fuels are concerned. Demand for residual fuels is expected to increase at a rate higher than that of total energy use whereas gas demand is estimated to fall. Demand for electricity, by contrast is estimated to grow at roughly the rate of population growth. These growth differentials are largely explained by the corresponding fuel price inflation differentials.

The growth rate of total energy demand and emissions is estimated to fall to around 0.6 per cent per annum in the case of DOLS and S-AI but to -0.3 per cent from 1.06 per cent in the case of the VECM representation. The relatively greater abatement in the case of the VECM representation, however, is not credible as this estimator found significant complementarity between electricity and gas. The growth rates of electricity and residual fuels demand and emissions is predicted to fall relative to the baseline scenario across the three estimators, but the behaviour of gas is not consistent across estimators largely because of differences in the estimates of cross-fuel price elasticities.

It should be noted that the demand elasticities presented in this paper are long-run. In the short-run, when energy appliances are fixed, the price sensitivities are expected to be rather small and it may take a number of years for a significant adjustment to take place in response to a given price change. Changes in electricity consumption, and therefore in carbon emissions, is expected to be minor in the short-run in response to any policy change.

Notes

[1] This tax rate roughly corresponds to a tax rate of US$200 per tonne of carbon, in 1992 dollars, as analysed by Brown *et al.* (1999) to assess the impact of the Kyoto protocol on various regions including Australia.

[2] Information on CO_2 emission factors, oxidation factors and actual CO_2 emissions between 1990 and 1997 were obtained from National Greenhouse Gas Inventory Committee (NGGIC 1999).

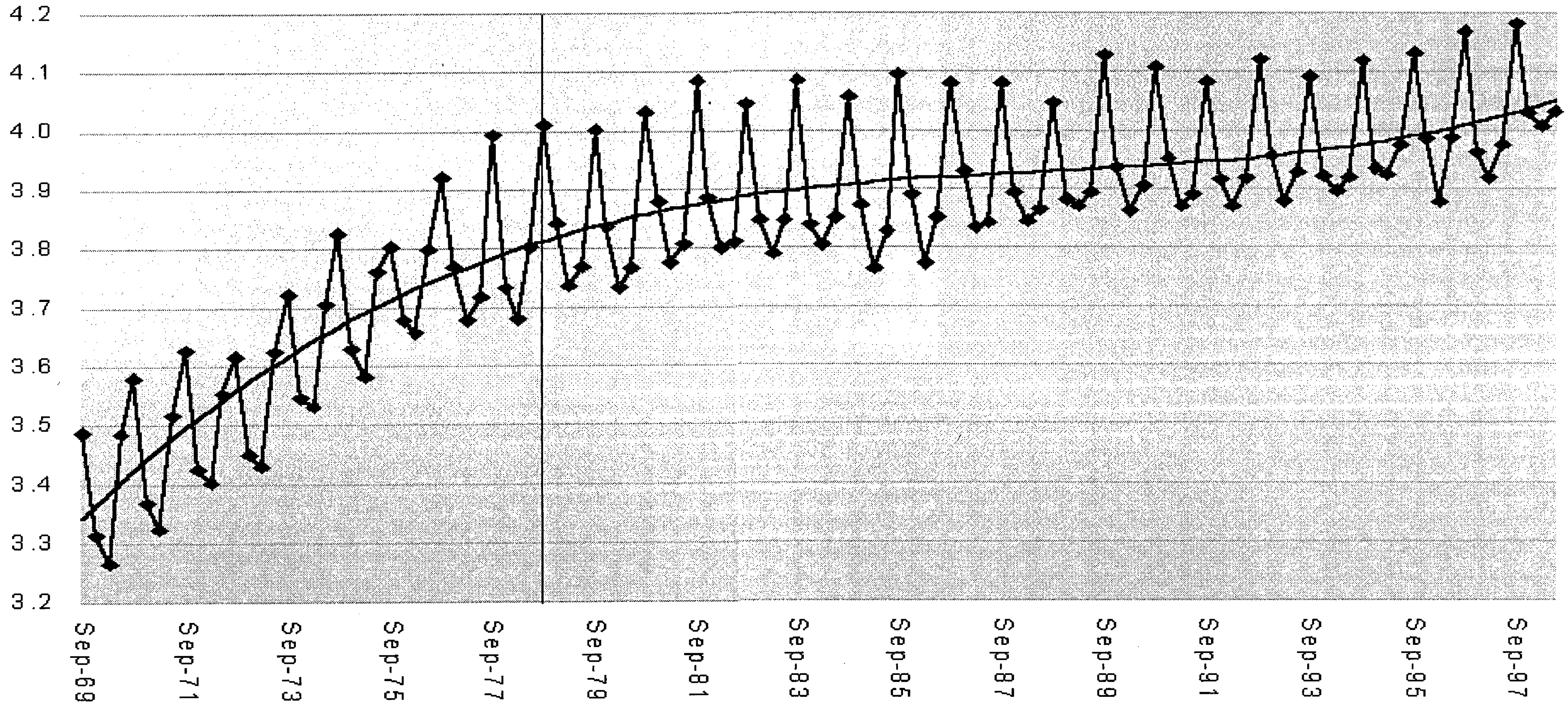
[3] It is, however, worth mentioning that with the increasing penetration of air-conditioning many areas of Australia are moving towards summer peaks.

[4] This rule is suggested and used by Perron (1989).

[5] The order of the underlying VAR model is chosen using Akaike's information criterion. A maximum order of five is considered following the simple rule of $N^{1/3}$, where N is the sample size (116). Residual autocorrelations from the selected VARs were examined and found to be insignificant.

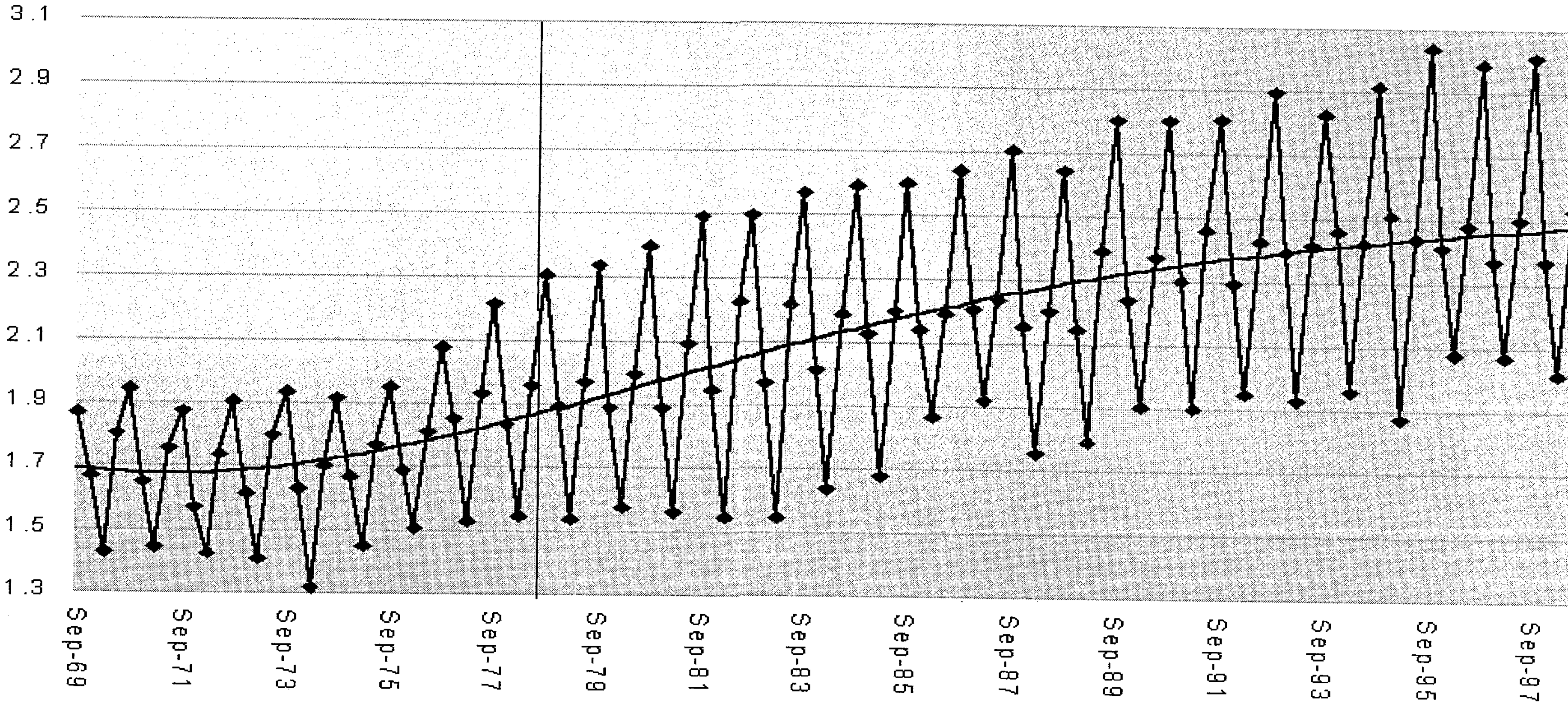
[6] The electricity price increases by roughly three-quarters, the gas price by one-half and the residual fuels price nearly doubles between 1998 and 2010.

Appendix Figure A4.1 **Real expenditure on electricity** (log)



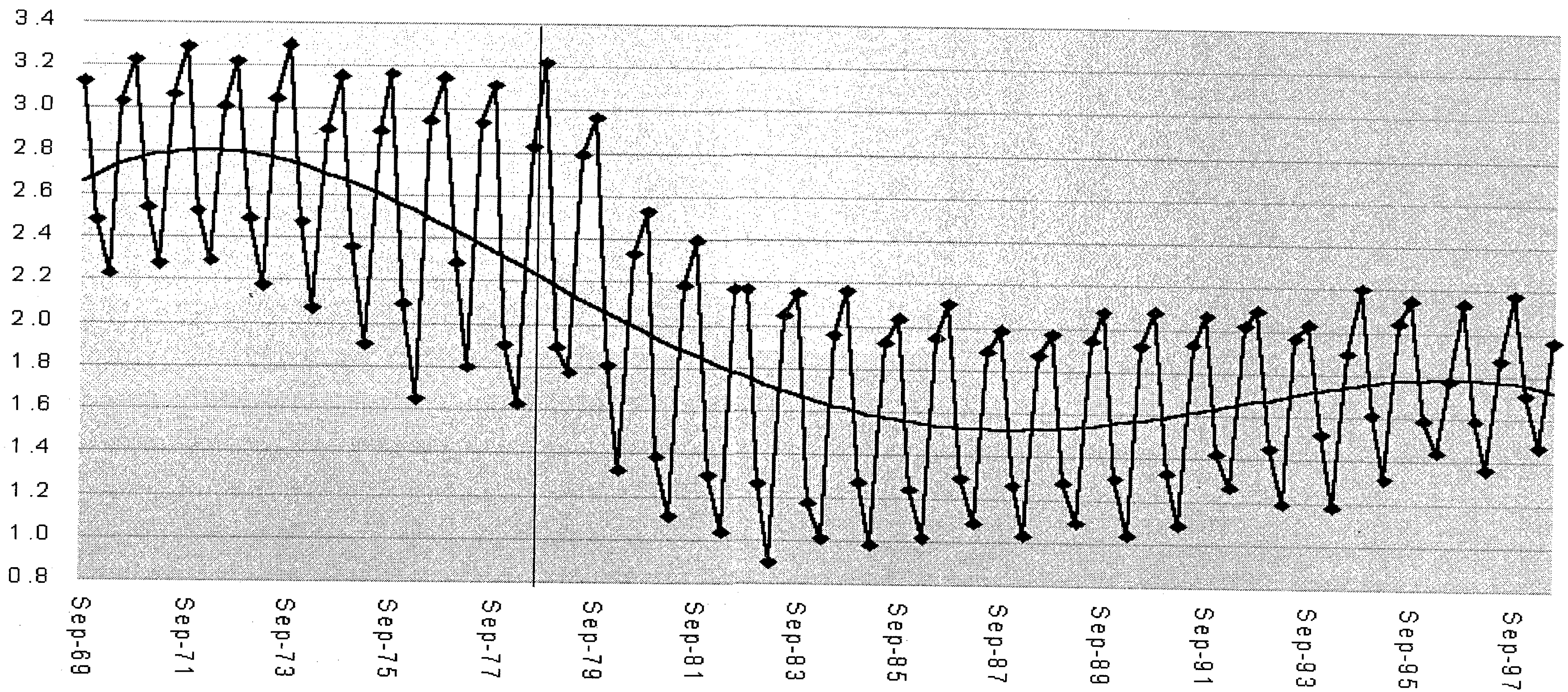
Sources Australian Bureau of Statistics, 1999. *Australian National Accounts: national income, expenditure and product,* Catalogue No. 5206.0, Canberra; author's calculations.

Appendix Figure A4.2 **Real expenditure on gas (log)**



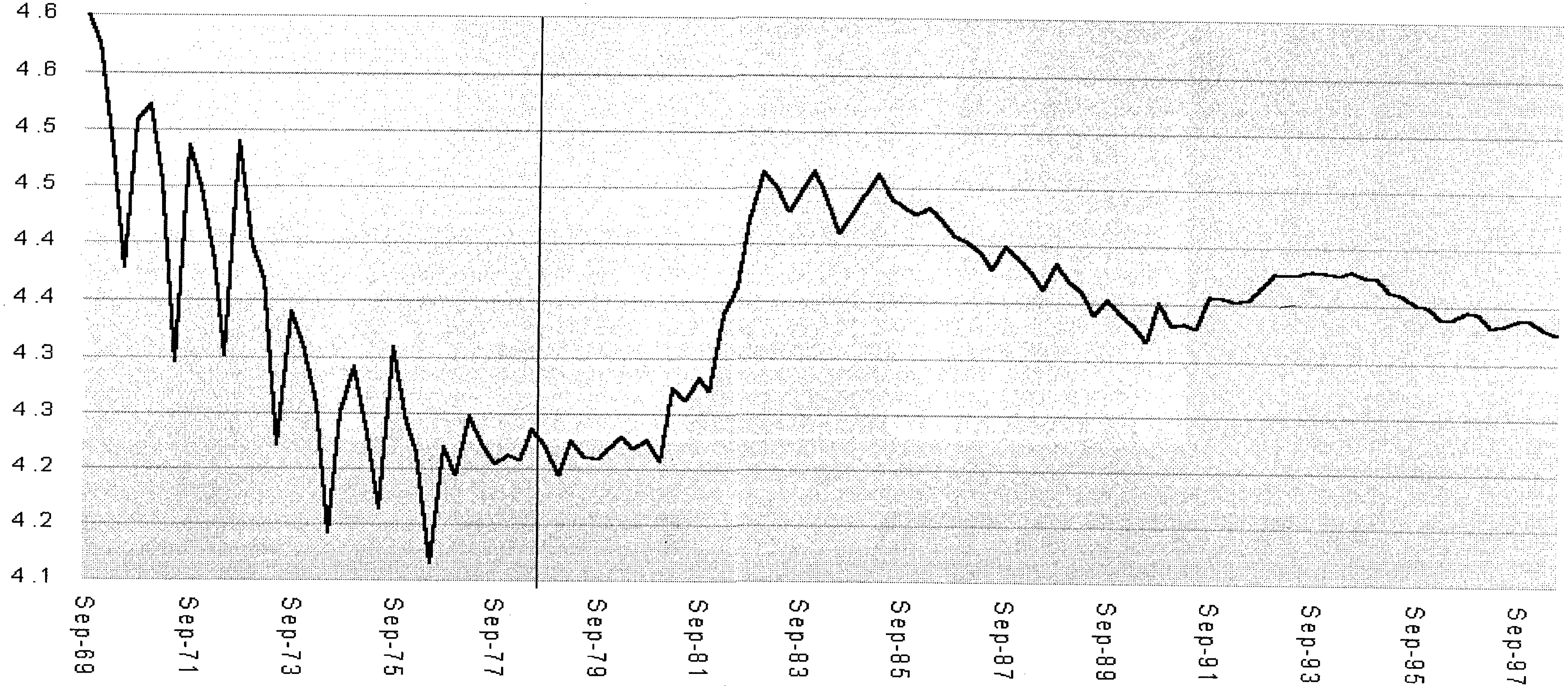
Sources: Australian Bureau of Statistics, 1999. *Australian National Accounts: national income, expenditure and product,* Catalogue No. 5206.0, Canberra; author's calculations.

Appendix Figure A4.3 **Real expenditure on residual fuels (log)**



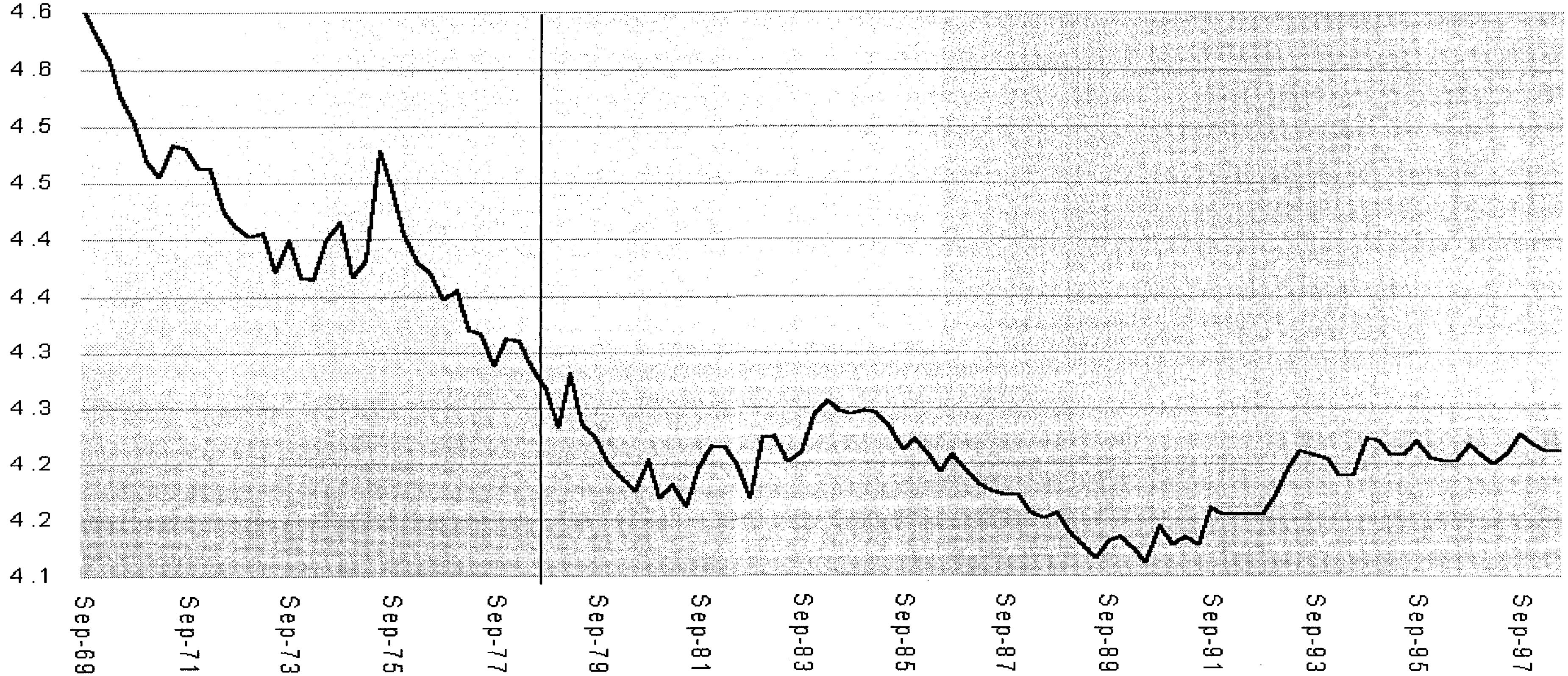
Sources: Australian Bureau of Statistics, 1999. *Australian National Accounts: national income, expenditure and product,* Catalogue No. 5206.0, Canberra; author's calculations.

Appendix Figure A4.4 **Real electricity price index (log)**



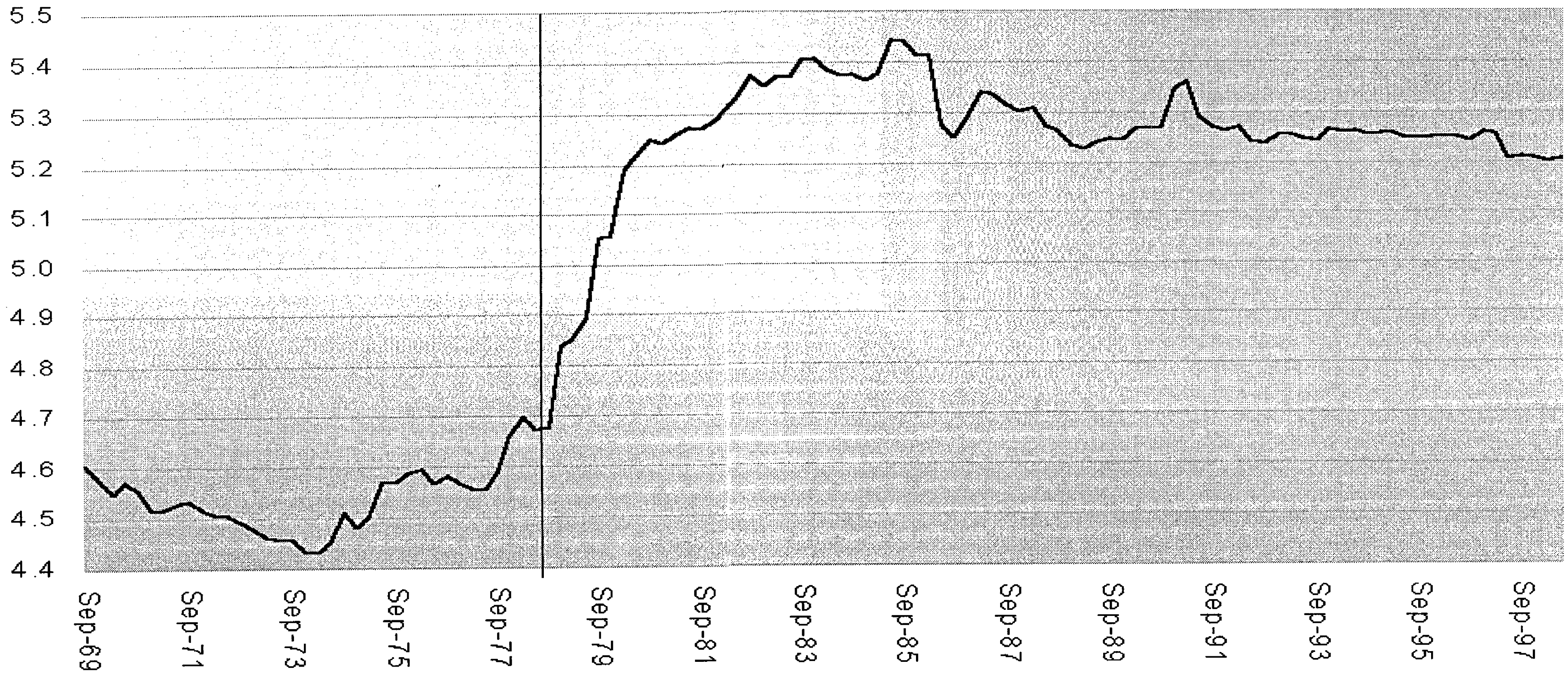
Sources Australian Bureau of Statistics, 1999. *Australian National Accounts: national income, expenditure and product,* Catalogue No. 5206.0, Canberra; author's calculations.

Appendix Figure A4.5 **Real gas price index** (log)



Sources: Australian Bureau of Statistics, 1999. *Australian National Accounts: national income, expenditure and product*, Catalogue No. 5206.0, Canberra; author's calculations.

Appendix Figure A4.6 **Real residual fuels price index (log)**



Sources: Australian Bureau of Statistics, 1999. *Australian National Accounts: national income, expenditure and product*, Catalogue No. 5206.0, Canberra; author's calculations.

Appendix Table A4.1 **Regression results, electricity**

Variables	Parameters	Standard error	t-score
α	0.1869	0.2559	0.73
p_1	-0.9515	0.0768	-12.39
p_2	0.2052	0.0902	2.28
p_3	0.3767	0.0302	12.49
y	0.5226	0.0460	11.37
d_1	-0.0345	0.0513	-0.67
d_2	0.1239	0.0649	1.91
d_3	0.3391	0.0719	4.72
Lags			
One			
p_1	0.1443	0.0858	1.68
p_2	-0.1868	0.1500	-1.25
p_3	-0.2828	0.0918	-3.08
y	-0.5700	0.2625	-2.17
Two			
p_1	-0.1519	0.0808	-1.88
p_2	-0.0873	0.1701	-0.51
p_3	-0.3505	0.0548	-6.40
y	-0.3310	0.2496	-1.33
Three			
p_1	0.2792	0.0892	3.13
p_2	0.1733	0.1171	1.48
p_3	-0.1838	0.0561	-3.28
y	-0.3398	0.2571	-1.32
Four			
p_1	0.2332	0.0799	2.92
p_2	0.2810	0.1354	2.08
p_3	-0.3287	0.0656	-5.01
y	-0.5645	0.2493	-2.26
Five			
p_1	0.1053	0.0898	1.17
p_2	0.1997	0.0959	2.08
p_3	-0.0856	0.0399	-2.15
y	-1.0624	0.2731	-3.89
Six			
p_1	0.0998	0.0897	1.11
p_2	0.0240	0.0896	0.27
p_3	-0.2247	0.0450	-5.00
y	-0.2264	0.3166	-0.72
Leads			
One			
p_1	-0.2863	0.1298	-2.21

p_2	0.3570	0.1158	3.08
p_3	0.1738	0.0495	3.51
y	-1.3572	0.2566	-5.29
Two			
p_1	-0.5430	0.0939	-5.79
p_2	0.1440	0.1122	1.28
p_3	0.2588	0.0893	2.90
y	-0.6825	0.3440	-1.98
Three			
p_1	-0.2707	0.1086	-2.49
p_2	-0.2044	0.1139	-1.80
p_3	0.0992	0.0770	1.29
y	-0.1686	0.2498	-0.68
Four			
p_1	-0.3573	0.0912	-3.92
p_2	0.0529	0.0986	0.54
p_3	0.1615	0.0695	2.33
y	-0.3868	0.2245	-1.72
Five			
p_1	-0.2392	0.0659	-3.63
p_2	-0.2703	0.1036	-2.61
p_3	0.2333	0.0671	3.48
y	-0.2501	0.2099	-1.19
Six			
p_1	-0.2465	0.0878	-2.81
p_2	-0.2349	0.1256	-1.87
p_3	0.0640	0.0832	0.77
y	0.1387	0.3018	0.46

Note: $R^2 = 0.9909$, $\overline{R}^2 = 0.9805$.
Source: Author's estimations.

Appendix Table A4.2 **Regression results, gas**

Variables	Parameters	Standard error	t-score
α	-9.4966	0.4723	-20.11
p_1	0.8704	0.1214	7.17
p_2	-0.7021	0.2155	-3.26
p_3	-0.1864	0.0583	-3.20
y	1.8821	0.0799	23.55
d_1	-0.3483	0.1247	-2.79
d_2	0.0185	0.0895	0.21
d_3	0.4376	0.1078	4.06
Lags			
One			
p_1	-0.9563	0.1778	-5.38
p_2	-0.1550	0.3931	-0.39
p_3	0.2801	0.1723	1.63
y	-0.5410	0.9462	-0.57
Two			
p_1	0.2244	0.1943	1.16
p_2	-0.4338	0.3367	-1.29
p_3	0.2145	0.1736	1.24
y	-0.9677	0.6051	-1.60
Leads			
One			
p_1	0.5012	0.1843	2.72
p_2	-0.5638	0.3092	-1.82
p_3	-0.1870	0.1833	-1.02
y	0.6913	0.7580	0.91
Two			
p_1	0.9696	0.2054	4.72
p_2	0.1492	0.3751	0.40
p_3	0.1660	0.1767	0.94
y	-0.3312	0.6169	-0.54

Note: $R^2 = 0.9909$, $\overline{R}^2 = 0.9805$.
Source: Author's estimates.

Appendix Table A4.3 **Regression results, residual fuels**

Variables	Parameters	Standard error	t-score
α	-1.1067	0.7329	-1.51
p_1	0.9867	0.3280	3.01
p_2	1.2947	0.4727	2.74
p_3	-1.1681	0.1687	-6.93
y	0.5377	0.1321	4.07
d_1	0.3595	0.2650	1.36
d_2	2.1074	0.3902	5.40
d_3	1.3402	0.3678	3.64
Lags			
One			
p_1	-0.4683	0.3033	-1.54
p_2	-1.5820	0.4751	-3.33
p_3	1.0020	0.3126	3.21
y	1.3048	1.0050	1.30
Two			
p_1	0.2218	0.3031	0.73
p_2	-2.0515	0.3827	-5.36
p_3	1.5406	0.2524	6.10
y	4.7326	1.4760	3.21
Three			
p_1	-0.6023	0.2333	-2.58
p_2	0.1909	0.6139	0.31
p_3	0.6440	0.2467	2.61
y	-0.6506	1.1010	-0.59
Four			
p_1	0.2411	0.3589	0.67
p_2	-1.0815	0.3840	-2.82
p_3	0.1358	0.2246	0.60
y	-3.4989	1.0240	-3.42
Five			
p_1	-0.1361	0.4051	-0.34
p_2	-2.1814	0.4061	-5.37
p_3	0.6668	0.2810	2.37
y	-0.0065	0.9749	-0.01
Six			
p_1	-0.5523	0.3526	-1.57
p_2	-0.4805	0.4591	-1.05
p_3	0.6899	0.3528	1.96
y	0.5006	1.5430	0.32
Leads			
One			
p_1	0.9868	0.3930	2.51

p_2	-0.4180	0.3983	-1.05
p_3	-0.2869	0.2596	-1.11
y	-1.3857	1.1200	-1.24
Two			
p_1	1.3325	0.2618	5.09
p_2	1.2651	0.4407	2.87
p_3	0.4918	0.3065	1.60
y	-1.6559	1.2800	-1.29
Three			
p_1	0.4052	0.3477	1.17
p_2	1.1340	0.5250	2.16
p_3	1.0069	0.3280	3.07
y	2.0289	1.3900	1.46
Four			
p_1	0.4145	0.3551	1.17
p_2	-0.6754	0.4931	-1.37
p_3	0.5002	0.3120	1.60
y	0.9502	1.0920	0.87
Five			
p_1	-0.2520	0.4185	-0.60
p_2	0.5143	0.3680	1.40
p_3	-0.3716	0.3742	-0.99
y	-0.7180	0.9827	-0.73
Six			
p_1	0.0888	0.3484	0.25
p_2	2.3922	0.6034	3.96
p_3	-0.2340	0.3335	-0.70
y	-0.3452	1.2780	-0.27

Note: $R^2 = 0.9909$, $\overline{R}^2 = 0.9805$.
Source: Author's estimations.

5

The deadweight loss of a carbon tax: an analysis using the almost ideal demand system

Synopsis

The Almost Ideal (AI) demand system covering electricity, gas, other fuels and non-fuel household consumption expenditure is re-estimated in this chapter after incorporating local curvature conditions with a view to analysing the deadweight loss of a carbon tax. The curvature-restricted system is applied to three data sets – national-level annual data, national-level quarterly data and a state-level quarterly panel data set. The welfare analysis assumes constant returns to scale and thus perfectly elastic supply conditions and a complete tax pass-through. The carbon tax revenue is assumed to be re-cycled in the form of a payroll tax deduction, leaving the general and non-fuel price levels unchanged. In these circumstances and using annual data, a tax of $300 per tonne of carbon is estimated to result in a deadweight loss of $495 million, approximately 7 per cent of total household fuel expenditure. For the corresponding national-level quarterly specification, the net welfare loss falls 2.7 per cent to $482 million and to $434 million for the state-level panel data-based demand parameters.

5.1 Introduction

The closely related issues of energy demand and greenhouse gas (GHG) emissions have attracted a great deal of attention in recent years because of the so-called greenhouse effect. A significant amount of effort has been expended, for instance, on understanding the role of energy in various production processes. The main aim, in this connection, has been to enhance understanding of the potential substitution from energy to non-energy factors of production and, within energy factor inputs, from more carbon intensive to less carbon intensive fuels.

As a result, many studies have focused on modelling consumer energy demand with a view to quantifying the substitution possibilities between different energy sources and between energy and non-energy commodities. These estimates of the consumer and input demand structure are being increasingly used to analyse the impact of a carbon tax – a pollution control instrument considered to be the easiest one to implement and monitor – on welfare, energy demand and associated GHG emissions.[1]

This chapter has two main aims. First, it reports the results of modelling the consumer demand for various fuels along with that of non-fuel household consumption expenditure. Second, it analyses the deadweight loss (DWL) from implementing a carbon tax. The first question has already been addressed at length in Chapter 3, where three applications of the AI demand system were reported. In order to attempt the second question, it is crucial that the underlying expenditure function be concave, at least for the most recent quarter/year included in the sample.[2] However, in the previous estimates, the Slutsky matrix (SM) frequently failed to satisfy the conditions of negative semidefiniteness. In this chapter, the static AI model is re-estimated after incorporating curvature conditions in the neighbourhood of 1998, the last sampled year.

The impact of a tax of $300 per tonne of carbon under perfectly horizontal supply conditions[3] increases the price of electricity by 72 per cent, that of gas by 53 per cent and of other fuels by 88 per cent. The impact of the carbon tax on the general consumer price level is assumed to be zero, because of the assumption of carbon tax recycling in the form of a payroll tax deduction.[4]

The rest of the chapter is organised as follows. Section 5.2 briefly reviews the studies which have analysed in the Australian context the impact of taxes, especially a carbon tax, on welfare.[5] Section 5.3 begins with a brief discussion of the AI demand system followed by a diagrammatic exposition of the measurement of the DWL of commodity taxation. The results, both relating to demand parameters and welfare costs, are presented and discussed in Section 5.4. Finally, the study is summarised in Section 5.5.

5.2 Literature review

The Australian literature on the impact of fuel taxes is dominated by two researchers: John Creedy – the Truby Williams Professor of Economics at the University of Melbourne, and Antonia Cornwell who is at the Industry Commission, Melbourne.[6] Using simulation models developed by Creedy (1992) and Cameron and Creedy (1995), Cornwell and Creedy (1996a) examine the effects of a domestic fuel use tax in Australia on income inequality, tax regressivity and social welfare. The study investigates only the impact effects of tax changes, as it does not incorporate behavioural responses to price changes caused by the tax. The analysis is performed both in cross-sectional and life-cycle frameworks. The likely effect of the tax, according to the authors, is small, both in cross-sectional and life-cycle frameworks. More precisely, the results indicate that the effect of a 30 per cent domestic fuel use tax, as measured by the impact effects, is smaller than the effect of a 15 per cent food tax. When the authors adjust transfer payments to maintain revenue neutrality, the regressivity of the tax is more than compensated.

In another paper, Cornwell and Creedy (1996b) investigate the level of carbon tax required to meet the Toronto target – 20 per cent reduction in greenhouse gas emissions from the 1988 emission levels by 2005. The authors also analyse the distributional and welfare consequences of the tax. The analysis allows not only for consumer responses to price variations but also takes into account the effects of substitution in production, although in an arbitrary fashion. The authors find that a tax of US$306 per tonne of carbon meets the target but at the cost of a reduction in the degree of tax progressivity, an increase in inequality and a loss of welfare.

In two other studies – Cornwell and Creedy (1995) and Cornwell and Creedy (1997b) – the two authors use the linear expenditure system (LES) to analyse the welfare implications of price changes caused by a carbon tax designed to reduce the carbon emissions. The LES is applied to each of a range of household income groups and not to a representative consumer. The production structure is characterised by a Leontief technology and all the greenhouse abatement arises from substitution in consumption. The authors find that a carbon tax, with a given level of income transfers, unambiguously decreases welfare across all income brackets. The effect of the tax, however, becomes ambiguous when the authors raise the level of transfers with the tax, with a view to compensating the low-income groups.[7]

Albon (1998) investigates the efficiency effects of the diesel fuel rebate scheme, which returns most of the excise tax on diesel fuel used off-road by agricultural and mineral producers. Removal of the rebate, the author argues, could cause three inefficiencies: 1) input-output distortions, 2) deadweight loss on account of reduced exports, and 3) flow-on inefficiencies in domestic manufacturing. There are, on the other hand, the author notes, two possible sources of efficiency gains: 1) less (other) distorting taxes; and 2) reduction in compliance and administration costs. The author argues that removing the rebate scheme could possibly lead to a \$1 billion reduction in GDP in order to raise just \$570 million in net revenue.

To the best of this author's knowledge, there has been no study of the welfare implications of a carbon tax for the Australian economy using flexible demand systems. This study estimates the net welfare loss of a carbon tax using the AI demand system – the most popular among the family of flexible commodity demand systems – and three data sets, including a panel data set.

5.3 Methodology

5.3.1 Demand system

Following Deaton and Muellbauer (1980), the linear approximate AI demand system is written as:

$$w_i = \gamma_i + \sum_{j=1}^{n} \gamma_{ij} \log p_j + \beta_i \log\left(\frac{x}{P}\right) \tag{5-1}$$

where w_i is the ith budget share; p_i denotes the price of the ith commodity; x is per capita expenditure on n commodities; $\log P = \sum_{i=1}^{n} w_i \log(p_i)$ and the γs and βs are the unknown parameters.[8] The adding-up, homogeneity and symmetry properties require the following restrictions:

$$\sum_{i=1}^{n} \gamma_i = 1,\ \sum_{i=1}^{n} \beta_i = 0, \sum_{i=1}^{n} \gamma_{ij} = 0 \qquad \text{(adding-up)} \tag{5-2}$$

$$\sum_{j=1}^{n} \gamma_{ij} = 0 \qquad \text{(homogeneity)} \tag{5-3}$$

$$\gamma_{ij} = \gamma_{ji} \qquad \text{(symmetry)} \tag{5-4}$$

The elements of the Slutsky matrix[9] are given by:

$$S_{ij} = \frac{x}{p_i p_j}\left[\gamma_{ij} + w_i w_j - \delta_{ij} w_i + \beta_i \beta_j \log\left(\frac{x}{P}\right)\right] \tag{5-5}$$

where δ_{ij} is the Kronecker delta which takes a value of 1 for $i=j$ and zero otherwise. Following Moschini (1998) and Ryan and Wales (1998), the above matrix is restricted to be negative semidefinite for 1998, the last sampled year, for the annual model and in the neighbourhood of the fourth quarter 1997 for the corresponding quarterly specification. The panel data-based expenditure function is restricted to be concave in prices for the fourth quarter 1997, and corresponding to the Western Australian state.[10]

The compensated (Hicksian), ϖ_{ij}, and the uncompensated (Marshallian), ε_{ij}, price elasticities of demand are computed from:

$$\varepsilon_{ii} = -1 + \gamma_{ii} / w_i - \beta_i, \;\; i = 1,2,\ldots\ldots\ldots\ldots,n \tag{5-6}$$

$$\varepsilon_{ij} = \gamma_{ij} / w_i - \beta_i (w_j / w_i), \;\; i,j = 1,2,\ldots\ldots\ldots,n; \;\; i \neq j \tag{5-7}$$

$$\varpi_{ii} = -1 + \gamma_{ii} / w_i + w_i, \;\; i = 1,2,\ldots\ldots\ldots\ldots,n \tag{5-8}$$

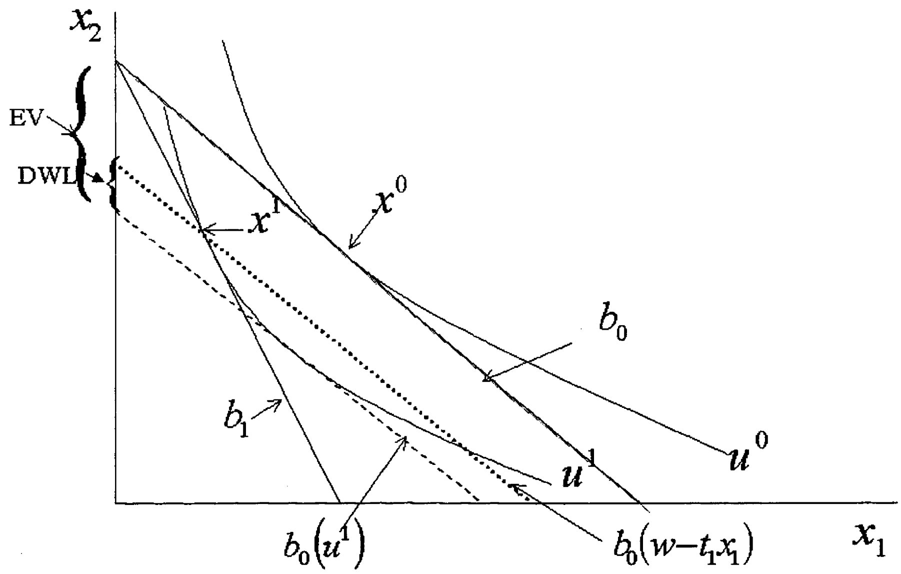
$$\varpi_{ij} = \gamma_{ij} / w_i + w_j, \;\; i,j = 1,2,\ldots\ldots\ldots\ldots,n; \;\; i \neq j \tag{5-9}$$

The above demand system in (5-1) is estimated using three data sets for $n = 4$; where 1 = electricity, 2 = gas, 3 = other fuels and 4 = non-fuel household consumption expenditure as defined previously. The first data set is an annual one spanning the period from 1970 to 1998. The second is the corresponding quarterly data from the third quarter 1969 to the second quarter 1998. And, finally, the system is estimated using state-level quarterly data from the third quarter 1984 to the second quarter 1998 on a panel of five states.[11]

5.3.2 Welfare analysis

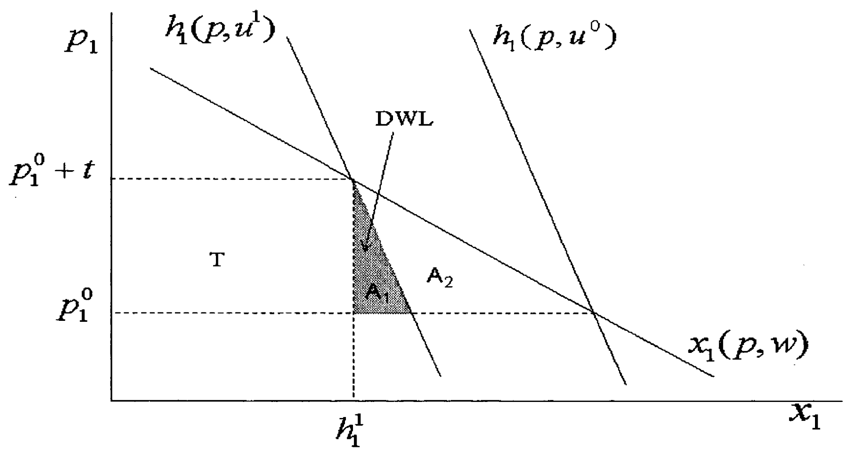
The deadweight loss of commodity taxation is defined as the extra amount by which the consumer is made worse off by the taxation above what is necessary to raise the same revenue by a lump-sum tax (Mas-Colell *et al.*, 1995:84-7). In more simple terms the deadweight loss of commodity taxation may be defined as a net loss to society induced by a discrepancy between prices charged and the corresponding efficient prices. This can be explained with the help of a two-space diagram (Figure 5.1). Imagine there are two commodities, x_1 and x_2, with the corresponding prices p_1 and p_2, respectively and a wealth level w. x_2 is a numeraire commodity with a unit price, p_2. The consumer is initially in equilibrium with the commodity bundle x^0. A tax on x_1 of t_1 per unit leads to a new equilibrium with the commodity bundle x^1. This new bundle lies not only on the new steeper budget line, b_1, but also on the budget line associated with the budget set $p_1 x_1(p,w) + p_2 x_2(p,w) = w - t_1 x_1(p,w)$. The budget line that generates the post price change utility (u^1) lies, in contrast, below this budget line. Total welfare loss, in dollar terms, caused by the commodity tax, is given by the vertical distance between the original budget line b_0 and a hypothetical budget line $b_0(u')$ that generates lower level of utility u'. The tax revenue raised, however, is given by the vertical distance between b_0 and $b_0(w-t_1x_1)$. The deadweight loss of the tax, therefore, is the vertical distance between the two broken budget lines (Figure 5.1).

Figure 5.1 **The deadweight loss, an illustration**



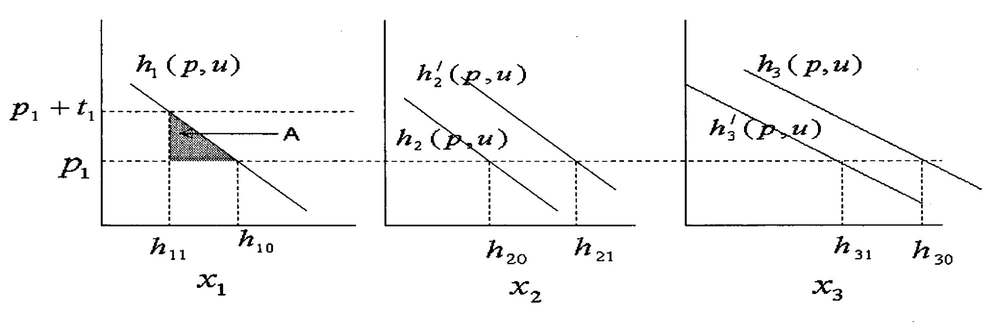
Alternatively, the net welfare cost of commodity taxation can be viewed as area behind the compensated demand curve. In Figure 5.2, $x_1(p,w)$ is the Marshallian demand function, whereas $h_1(p,u^1)$ is the corresponding Hicksian demand function associated with the post-price change level of utility, u^1. The DWL is the shaded area, A_1, under the Hicksian demand curve. The corresponding area behind the Marshallian demand curve ($A_1 + A_2$) is not an 'exact' measure of the net welfare loss, owing to a contamination by the varying income along the ordinary demand curve. The area T plus the DWL is the equivalent variation (EV) – the dollar amount that to the consumer is equivalent to the price increase in terms of its impact on welfare – of the price change caused by the tax. The EV in Figure 5.1 is given by the vertical distance between the pre-price change budget line, b_0, and the budget line denoted by $b_0(u^1)$.

Figure 5.2 **The deadweight loss, another representation**



In order to arrive at a general expression for the DWL of commodity taxation, the Harberger (1974) procedure is followed. It is assumed, purely for illustrative purposes, that there are three commodities (actual analysis considers four goods – three fuels and a composite good). The Hicksian demands are represented by $h_1(p,u)$, $h_2(p,u)$ and $h_3(p,u)$, whereas the corresponding Marshallian demand functions are denoted by $x_1(p,w)$, $x_2(p,w)$ and $x_3(p,w)$. Without loss of generality, the constant marginal cost is assumed to be the same across the three commodities (Figure 5.3). Good one and good three are considered complementary goods in the Hicksian sense, whereas the other pairs are assumed to be substitutes.

Figure 5.3 **The deadweight loss computation, stage 1**



Further, it is assumed that a tax of $\$t_1$ per unit is imposed on commodity one in a situation where there is no tax or any other distortion in the other two markets. As a consequence, the constant marginal cost function in Figure 5.3a shifts upwards to $p_1 + t_1$ to fully reflect the tax. The demand functions in Figure 5.3b and Figure 5.3c shift to $h_2'(p,u)$ and $h_3'(p,u)$, respectively. The DWL at this stage, DWL_1, occurs only in the first market, which is given by the triangle denoted by A. There is no welfare loss in the other two markets, as the marginal valuations are still equal to the marginal costs. This first stage loss is approximated by:

$$DWL_1 = -\frac{1}{2} t_1 (h_{11} - h_{10}) \tag{5-10}$$

In terms of the Hicksian demand parameters the DWL_1 is:

$$DWL_1 = -\frac{1}{2} t_1 \frac{\partial h_1}{\partial p_1} dp_1 \tag{5-11}$$

Noting that $\partial h_1 / \partial p_1$ is defined previously as S_{11} in (5-5) and that dp_1 equals t_1, the above expression is simplified to:

$$DWL_1 = -\frac{1}{2} S_{11} t_1^2 \tag{5-12}$$

Things become interesting when a tax of $\$t_2$ is imposed on x_2 in the presence of a tax on the first commodity. The marginal cost function in Figure 5.4b shifts upwards to $p_2 + t_2$ and the demand functions in Figure 5.4a and Figure 5.4c shift to the right to $h_1^{//}(p,u)$ and $h_3^{//}(p,u)$, respectively. The welfare loss that occurs in the market for x_2 is given by the triangle B.[12] However, in the first market, welfare improves due to the fact that the two commodities are substitutes. The welfare gains in this market, given by the rectangle C, are realised as the marginal valuation of x_1 is given by p_1+t_1 whereas the corresponding marginal cost to society of producing an extra unit of the commodity is still p_1.

It is quite likely that welfare may indeed improve on account of extending the tax to the second commodity if the two commodities are good substitutes given relative tax rates and other demand parameters. The net welfare loss at this second stage is approximated by:

$$DWL_2 = -B - C = -\frac{1}{2} t_2 (h_{22} - h_{21}) - t_1 (h_{12} - h_{11}) \tag{5-13}$$

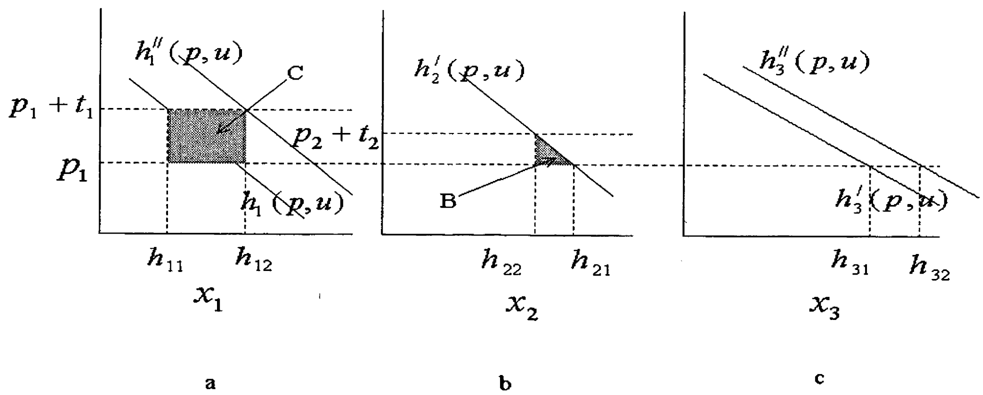
Alternatively, the two areas in Figure 5.4a and Figure 5.4b, are given by:

$$DWL_2 = -\frac{1}{2} t_2 \frac{\partial h_2}{\partial p_2} dp_2 - t_1 \frac{\partial h_1}{\partial p_2} dp_2 \tag{5-14}$$

Noting, again, that $\partial h_i / \partial p_j = S_{ij}$ and that $dp_i = t_i$, the second stage welfare loss is written as:

$$DWL_2 = -\frac{1}{2} S_{22} t_2^2 - S_{12} t_1 t_2 \tag{5-15}$$

Figure 5.4 **The deadweight loss computation, stage 2**



Finally, a tax of $\$t_3$ is imposed on x_3 in the presence of a tax on x_1 and x_2. In order to keep things simple, only the final stage curves from Figure 5.4 are reproduced in Figure 5.5. A tax of $\$t_3$ shifts the marginal cost function upwards in Figure 5.5c by the full amount of per unit tax to $p_3 + t_3$. As a result, the demand function in Figure 5.5a shifts to the left to $h_1^{///}(p,u)$ and that in Figure 5.5b to the right to $h_2^{///}(u,p)$. The welfare cost at this third and final stage that occurs in the market for good three is given by the triangle D. A welfare gain is realised in the second market due to the fact that a tax on x_3 increases the demand for good two. The extra consumption is still valued at the tax inclusive price of $p_2 + t_2$ while the additional production comes at the marginal cost of $\$p_2$. This results in a welfare gain that is given by the rectangle E. Complementarity between h_1 and h_2, by contrast, implies a further welfare loss in market one, as a tax on good three leads to a reduction in the use of good one. The loss is given by the triangle F. The deadweight loss at this stage is given by:

$$DWL_3 = -D - E - F = -\frac{1}{2} t_3 (h_{33} - h_{32}) - t_2 (h_{23} - h_{22}) - t_1 (h_{13} - h_{12}) \tag{5-16}$$

or

$$DWL_3 = -\frac{1}{2} t_3 \frac{\partial h_3}{\partial p_3} dp_3 - t_1 \frac{\partial h_1}{\partial p_3} dp_3 - t_2 \frac{\partial h_2}{\partial p_3} dp_3 \tag{5-17}$$

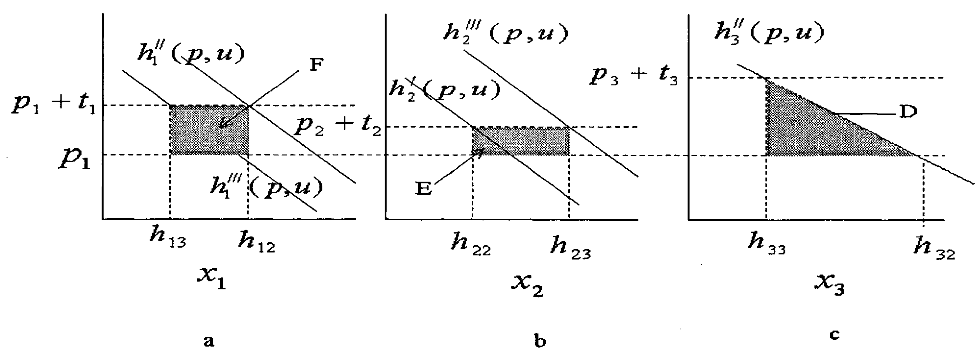
Using the Slutsky notation, the above expression becomes:

$$DWL_3 = -1/2 S_{33} t_3^2 - S_{13} t_1 t_3 - S_{23} t_2 t_3 \tag{5-18}$$

Adding the three components gives the total DWL:

$$DWL = -1/2\left[S_{11} t_1^2 + S_{22} t_2^2 + S_{33} t_3^2 + 2S_{12} t_1 t_2 + 2S_{13} t_1 t_3 + 2S_{23} t_2 t_3\right] \tag{5-19}$$

Figure 5.5 **The deadweight loss computation, stage 3**



Extension to the n-commodity case is simple and the general expression is:

$$DWL = -1/2 \sum_{i=1}^{n} \sum_{j=1}^{n} S_{ij} t_{ij} \tag{5-20}$$

This study considers a tax of \$300 per tonne of carbon, which, depending on the carbon content of the three fuels, implies a 72 per cent increase in the electricity price, a 53 per cent increase in the gas price and a 88 per cent increase in the price of the residual fuels assuming perfectly elastic supply conditions.[13] The case of electricity merits some elaboration as electricity consumption itself is not carbon emitting. Rather, there is carbon emission at the generation stage. With a view to obtaining a CO_2 factor for electricity, the CO_2 emissions associated with the power generation sector are divided by the total electricity generated. The power production and CO_2 data for the period 1990 to 1997 were used to derive an average CO_2 factor for the fuel.[14]

The carbon tax revenue is assumed to be recycled in the form of a payroll tax reduction. The recycling assumption is invoked for the sake of convenience, as the empirical evidence on the subject suggests that an economy-wide carbon tax leaves income and general prices largely unchanged if the revenue is re-cycled as mentioned above.[15] As the non-fuel household consumption expenditure constitutes nearly 97 per cent of the total household consumption expenditure, it is assumed that the tax leaves the non-fuel price level unchanged.

5.4 Results

As mentioned above, the main aim of estimating the demand functions for various fuels in this chapter is to analyse the impact of a carbon tax on welfare. In this regard, the estimates of the DWL along with some demand parameters, including compensated and uncompensated demand elasticities, based on the national-level annual data are reported in Table 5.1. Before moving on to the welfare estimates, the demand parameters are briefly discussed, as this will help understand the DWL estimates. The compensated demand derivatives (elements of the Slutsky substitution matrix), along with eigenvalues of the matrix, are presented in the second panel of the table. All the four demand curves are downward sloping which is hardly surprising, as the curvature conditions are built in the estimation process.[16] The cross-price derivatives indicate that all fuel pairs except gas-other fuels are substitutes. The quasi-concavity restrictions are met, as eigenvalues are all non-positive.

The Hicksian demands are relatively steeper with the exception of other fuels, which, due to its inferior status, shows an opposite relationship in the two slopes. Difference in slopes is negligible in the case of the three fuels but drastic for the composite non-energy good; the estimated Marshallian elasticity for the latter commodity is -0.99 while the Hicksian estimate is close to zero, -0.006. These variations should not be surprising as nearly 98 per cent of household consumption expenditure chases the composite commodity.

Electricity-gas and electricity-other fuels are substitutes – both net and gross – as the cross-price elasticities involved are positively signed. The annual data based analysis in Chapter 3, on the other hand, found complementarity tendencies between these fuel pairs. Not surprisingly, therefore, the own-price elasticities in the present estimates are comparatively large (in absolute terms). The Marshallian elasticity of electricity demand, for instance, is -0.907, whereas in Chapter 3, Table 3.2, it is estimated at -0.69. The difference is even higher in the case of other fuels.

Given other factors, a relatively large own-price elasticity of a commodity implies a comparatively greater DWL on account of a tax on the commodity. This is simply because output will deviate more from an efficient level, following a significant reduction in demand. In the special case of a completely inelastic demand, there will be no DWL induced by the tax. The extension of tax to another commodity will mitigate the DWL in the first market if the goods are substitutes; mitigation will increase with the degree of substitutability. The DWL abates because an increase in the relative price of the second good increases demand in the first market towards the competitive level of output. On the other hand, a complementary relationship will increase the loss because the tax will further push the output of the first commodity away from efficient production.

As electricity-gas and electricity-other fuels are substitutes, a significant mitigation in DWL is expected when the carbon tax is extended to gas and other fuels in the presence of a tax on electricity. Similarly, the complementary relationship between gas and other fuels will increase the DWL.

Table 5.1 **The estimates of deadweight loss and demand parameters, national-level annual data**

Commodities	Electricity	Gas	Other fuels	Non-fuel	Row sum
	Harberger rectangles and triangles ($ million)				
Electricity	*1232.27*	-301.55	-794.52	0.00	136.20
Gas		*110.44*	225.83	0.00	336.27
Other fuels			*22.60*	0.00	22.60
Non-fuel				*0.00*	0.00
Column sum	1232.27	-191.11	-546.09	0.00	*495.07*
	Slutsky matrix ($)				
Electricity	*-256.09*	42.72	67.28	146.09	na
Gas	42.72	*-42.66*	-2.61	2.55	na
Other fuels	67.28	-2.61	*-31.17*	-33.50	na
Non-fuel	146.09	2.55	-33.50	*-115.14*	na
Eigenvalues	3.55E-13	-35.1678	-50.6868	-385.839	na
	Hicksian elasticities				
Electricity	*-0.895*	0.149	0.235	0.510	0.000
Gas	0.605	*-0.604*	-0.037	0.036	0.000
Other fuels	2.992	-0.116	*-1.386*	-1.490	0.000
Non-fuel	0.008	0.000	-0.002	*-0.006*	0.000
	Marshallian elasticities				
	Electricity	Gas	Other Fuels	Non-fuel	Income
Electricity	*-0.907*	0.146	0.234	-0.247	0.774
Gas	0.580	*-0.611*	-0.039	-1.533	1.603
Other fuels	3.023	-0.108	*-1.384*	0.422	-1.953
Non-fuel	-0.008	-0.004	-0.003	*-0.990*	1.005

Source: Author's estimations based on the national-level annual data.

The diagonal terms in the top panel of Table 5.1 represent the triangles in the terminology of the previous section while the off-diagonal elements are the rectangles (positive values indicate deadweight losses, negative numbers are deadweight abatements). A 72 per cent electricity price increase caused by the tax, assuming no taxes on the other two fuels and non-fuel consumption, is expected to result in a welfare loss of more than $1.2 billion, nearly one-quarter of total electricity expenditure in

1998. The application of a 53 per cent carbon tax on gas in the presence of the electricity tax results in a welfare gain of nearly \$200 million, despite a welfare loss of more than \$110 million on account of gas consumption (see column two, top panel of Table 5.1). Indeed, electricity demand increases as gas becomes more expensive, because the two fuels are substitutes in the Hicksian sense. The additional electricity consumption is valued at a rate higher than the constant marginal cost, because of a wedge between the producer and consumer prices caused by the tax, leading to a welfare gain that more than offsets the welfare cost in the gas market.

The welfare gains are even higher when the carbon tax is extended to the other fuels market (column three, top panel of Table 5.1). At this stage, the net welfare gain exceeds half a billion dollars. The DWL on account of the use of other fuels is relatively small, due mainly to its small share in total energy use. Complementarity between gas and other fuels causes a further decline in gas consumption due to the tax on other fuels and thus adds to the welfare loss. However, substantial welfare gains in the case of electricity, nearly \$800 million, more than offset the losses associated with gas and other fuels, leading to more than \$500 million net welfare gain at this stage.

There is no welfare cost, or, for that matter, welfare gain in the markets for non-fuel commodities because the non-fuel price level does not change owing to the assumption of tax recycling. Overall, with the carbon tax imposed on the three fuel sources, the welfare loss stands at \$495 million, slightly more than 7 per cent of total fuel expenditure during 1998.

The discussion now moves on to the corresponding results based on the national-level quarterly data. The deadweight loss estimates for the third quarter are presented in Table 5.2; along with the Slutsky matrix and the Marshallian and Hicksian elasticities estimated using quarterly data. While the own-price elasticities of electricity and gas demand in the present estimates (see panels three and four, Table 5.2) are fairly close to their quarterly data-based counterparts in Chapter 3, Table 3.5, other fuels demand is much less elastic in the present estimates. This is largely because of a sharply lower estimate – also insignificant – of the income elasticity of other fuels in the present case. In comparison with the annual data-based elasticities in Table 5.1, demand elasticities in Table 5.2 are generally small (in absolute terms). Also, electricity and gas are complements, whereas in the previous table the two fuels are substitutes. As mentioned above, the welfare loss is going to be higher on account of complementarity between the two fuels.

Table 5.2 **The estimates of deadweight loss and demand parameters for the third quarter 1997, national-level quarterly data**

Commodities	Electricity	Gas	Other fuels	Non-fuel	Row sum
	Harberger rectangles and triangles ($ million)				
Electricity	*261.132*	20.179	-164.932	0.000	116.379
Gas		*26.786*	-21.306	0.000	5.480
Other fuels			*114.437*	0.000	114.437
Non-fuel				*0.000*	0.000
Column sum	261.132	46.964	-71.801	0.000	*236.296*
	Slutsky matrix ($)				
Electricity	*-53.891*	-2.839	13.870	42.898	na
Gas	-2.839	*-10.274*	2.443	10.756	na
Other fuels	13.870	2.443	*-15.686*	-0.618	na
Non-fuel	42.898	10.756	-0.618	*-53.168*	na
Eigenvalues	9.59E-14	-11.6541	-22.5546	-98.8102	na
	Hicksian elasticities				
Electricity	*-0.659*	-0.035	0.170	0.524	0.000
Gas	-0.121	*-0.440*	0.104	0.457	0.000
Other fuels	1.132	0.201	*-1.282*	-0.051	0.000
Non-fuel	0.010	0.003	0.000	*-0.012*	0.000
	Marshallian elasticities				
	Electricity	Gas	Other fuels	Non-fuel	Income
Electricity	*-0.673*	-0.039	0.168	-0.208	0.753
Gas	-0.147	*-0.448*	0.100	-0.893	1.387
Other fuels	1.131	0.200	*-1.282*	-0.099	0.049
Non-fuel	-0.009	-0.003	-0.003	*-0.991*	1.005

Source: Author's estimations based on the national-level quarterly data.

During the third quarter 1997, a net welfare loss of $261 million is estimated to occur if the carbon tax is applied only to electricity (see column one, top panel of Table 5.2). Unlike the annual data-based findings, the extension of the tax to gas adds $47 million to the welfare loss (see column two, top panel of Table 5.2); $27 million because gas demand falls short of an efficient level; and $20 million because electricity demand moves further away from its efficient level. As argued above, complementarity between electricity and gas causes a $20 million welfare loss when the tax is imposed on gas use.

Substantial welfare gains are realised when the carbon tax is extended to other fuels, as both electricity and gas are substitutes for residual fuels in the Slutsky sense. The welfare gains at this stage on account of electricity are much higher than the corresponding gas-related gains, partly because of higher electricity consumption and partly because of the relatively greater sensitivity of electricity demand to the prices of other fuels. Total expenditure on electricity during the third quarter 1997 was nearly three times that on gas. The welfare loss of $236 million is roughly 11 per cent of the total fuel expenditure during the quarter, much higher than the annual figure of 7 per cent.

The overall welfare loss during the fourth quarter 1997 falls sharply to $65 million (Table 5.3). Two interrelated factors explain this nearly 75 per cent reduction in the DWL from the previous quarter: Firstly, fuel use, especially that of gas and other fuels, falls significantly because of the warm weather.[17] This is reflected in the relatively smaller magnitudes of the Slutsky elements (see panel two, Table 5.3). Secondly, electricity and gas demand is relatively less sensitive during this period, which further magnifies the welfare loss reducing effect. The residual fuel, in contrast, is significantly more sensitive in terms of own-price elasticity. It seems, however, that the lower fuel consumption factor has more than offset the sensitivity factor, leading to a reduction in the welfare loss.

Table 5.3 **The estimates of deadweight loss and demand parameters for the fourth quarter 1997, national-level quarterly data**

Commodities	Electricity	Gas	Other fuels	Non-fuel	Row sum
	Harberger rectangles and triangles ($ million)				
Electricity	*185.107*	23.588	-175.252	0.000	33.443
Gas		*5.649*	-22.572	0.000	-16.923
Other fuels			*48.122*	0.000	48.122
Non-fuel				*0.000*	0.000
Column sum	185.107	29.237	-149.703	0.000	*64.641*
	Slutsky matrix ($)				
Electricity	*-38.201*	-3.318	14.738	26.782	na
Gas	-3.318	*-2.167*	2.588	2.897	na
Other fuels	14.738	2.588	*-6.596*	-10.730	na
Non-fuel	26.782	2.897	-10.730	*-18.949*	na
Eigenvalues	-7.51E-14	-1.19E-10	-2.57818	-63.335	na
	Hicksian elasticities				
Electricity	*-0.566*	-0.049	0.218	0.397	0.000
Gas	-0.203	*-0.133*	0.158	0.177	0.000
Other fuels	5.186	0.911	*-2.321*	-3.776	0.000
Non-fuel	0.006	0.001	-0.002	*-0.004*	0.000
	Marshallian elasticities				
	Electricity	Gas	Other fuels	Non-fuel	Income
Electricity	*-0.576*	-0.052	0.218	-0.269	0.678
Gas	-0.226	*-0.138*	0.157	-1.397	1.604
Other fuels	5.235	0.922	*-2.319*	-0.421	-3.417
Non-fuel	-0.009	-0.003	-0.003	*-0.991*	1.005

Source: Author's estimates based on the national-level quarterly data.

The first quarter 1998 estimates show a further decline to $51 million from $65 million in the previous quarter (see Table 5.4). This reduction again is explained by the weather. The first quarter is the warmest quarter and, as a result, fuel consumption is the lowest during this period. Also, the Slutsky matrix is not negative semidefinite, as the Hicksian demand function for gas is positively sloped and one of the four eigenvalues is positive. As a result, the gas triangle shows an improvement in welfare, although relatively small.

Table 5.4 **The estimates of deadweight loss and demand parameters for the first quarter 1998, national-level quarterly data**

Commodities	Electricity	Gas	Other fuels	Non-fuel	Row sum
	Harberger rectangles and triangles ($ million)				
Electricity	*176.495*	21.916	-160.906	0.000	37.505
Gas		*-2.281*	-20.689	0.000	-22.970
Other fuels			*36.371*	0.000	36.371
Non-fuel				*0.000*	0.000
Column sum	176.495	19.635	-145.224	0.000	*50.906*
	Slutsky matrix ($)				
Electricity	*-36.424*	-3.083	13.531	25.749	na
Gas	-3.083	*0.875*	2.372	-0.168	na
Other fuels	13.531	2.372	*-4.985*	-10.826	na
Non-fuel	25.749	-0.168	-10.826	*-14.617*	na
Eigenvalues	4.754003	-1.42E-13	-0.74717	-59.1585	na
	Hicksian elasticities				
Electricity	-0.574	-0.049	0.214	0.409	0.000
Gas	-0.254	*0.072*	0.196	-0.014	0.000
Other fuels	8.806	1.545	*-3.246*	-7.105	0.000
Non-fuel	0.006	0.000	-0.003	*-0.003*	0.000
	Marshallian elasticities				
	Electricity	Gas	Other fuels	Non-fuel	Income
Electricity	*-0.584*	-0.051	0.214	-0.263	0.684
Gas	-0.280	*0.068*	0.195	-1.730	1.747
Other fuels	8.901	1.563	*-3.244*	-0.711	-6.508
Non-fuel	-0.009	-0.003	-0.003	*-0.991*	1.005

Source: Author's estimations based on the national-level quarterly data.

The estimates for the second quarter 1998 show a more than 2.5-fold increase in the welfare loss to $130 million (see Table 5.5). This is largely attributable to the more than doubling of the residual fuel DWL triangle, from $36 million in the first quarter to $95 million in the second quarter. Indeed, the residual fuel consumption increases nearly by two-thirds between the two quarters, leading to this large increase in the welfare loss.

Table 5.5 The estimates of deadweight loss and demand parameters for the second quarter 1998, national-level quarterly data

Commodities	Electricity	Gas	Other fuels	Non-fuel	Row sum
	Harberger rectangles and triangles ($ million)				
Electricity	*191.808*	22.339	-169.056	0.000	45.091
Gas		*11.203*	-21.736	0.000	-10.532
Other fuels			*95.417*	0.000	95.417
Non-fuel				*0.000*	0.000
Column sum	191.808	33.542	-95.375	0.000	*129.976*
	Slutsky matrix ($)				
Electricity	*-39.584*	-3.143	14.217	28.039	na
Gas	-3.143	*-4.297*	2.492	4.890	na
Other fuels	14.217	2.492	*-13.079*	-3.477	na
Non-fuel	28.039	4.890	-3.477	*-29.082*	na
Eigenvalues	-1.51E-13	-4.981048	-14.3326	-66.7284	na
	Hicksian elasticities				
Electricity	-0.582	-0.047	0.211	0.418	0.000
Gas	-0.175	*-0.241*	0.140	0.276	0.000
Other fuels	1.477	0.260	*-1.372*	-0.366	0.000
Non-fuel	0.006	0.001	-0.001	*-0.007*	0.000
	Marshallian elasticities				
	Electricity	Gas	Other fuels	Non-fuel	Income
Electricity	*-0.593*	-0.049	0.210	-0.259	0.691
Gas	-0.198	*-0.247*	0.137	-1.220	1.528
Other fuels	1.481	0.261	*-1.371*	-0.122	-0.249
Non-fuel	-0.009	-0.003	-0.003	*-0.991*	1.005

Source: Author's estimations based on the national-level quarterly data.

Interestingly, the overall welfare loss for the four quarters – $482 million – is fairly close to the corresponding national-level annual data based estimate of $495 million. The annual data-based price elasticities, especially the inter-fuel price elasticities, are generally large compared to their quarterly data counterparts. The uncompensated own-price elasticity of electricity in Table 5.1, for instance, is -0.91 while the corresponding quarterly data based elasticity ranges between -0.57 to -0.66 (Table 5.2 to Table 5.5). The own-price elasticity of other fuels, however, is higher (in absolute terms) in two quarters than the corresponding annual data-based estimate. Also, it is worth noting that electricity and gas are substitutes while gas and other fuels are complementary fuels for the annual model. The nature of the relationship between the two pairs is exactly opposite for the quarterly model. It seems that these variations in the elasticity estimates have been offsetting in their role as a determinant of welfare, giving a very similar overall welfare loss estimate.

The panel data elasticities are discussed briefly before moving on to the estimates of the welfare loss (Appendix Tables A5.1 to A5.20). Indeed, these elasticities are markedly different from the other two sets. This is hardly surprising as these were obtained using data from 1985 to 1998 – a period characterised by stable energy prices. The other two sets of estimates were obtained, as mentioned above, using data spanning from 1970 to 1998. Real energy prices moved greatly during this period of three decades, especially from 1974 to 1985, triggered by the two oil shocks of the 1970s.

Probably the most striking difference is in the relative magnitudes of the fuel own-price elasticities. The (uncompensated) electricity demand elasticity, for instance, is sharply lower (in absolute terms) than its counterparts based on the two national-level specifications. According to the national-level annual model, the electricity demand elasticity is -0.91, whereas, in the panel data specification, it is greater than -0.1 in nearly 50 per cent of cases.

The panel data estimates of the other two fuel elasticities, in contrast, are much higher (in absolute terms) than the corresponding national-level ones. For example, the average gas elasticity across the three states of Victoria, South Australia and Western Australia is roughly -2, which differs greatly from the annual model estimate of -0.61. In the other two states – New South Wales and Queensland – the difference is even larger, as the average gas elasticity for the two states is -7.6. Indeed, in these two states, the gas consumption is relatively small. The average gas share in total household consumption expenditure across the five states, for example, is 2.3 times higher than the corresponding gas share for New South Wales and nearly six times that of Queensland.

The case of other fuels is similar to that of gas. The own-price elasticity of the fuel is considerably higher in relation to the corresponding elasticities based on the national-level specifications. This is especially true for New South Wales and Queensland, where the average elasticity across the eight quarters is almost -15, which is in sharp contrast to the average elasticity of -2.1 for the quarterly model. The other fuel consumption in the two states is significantly lower than the average residual fuel consumption across the five states, which probably explains the unusually large sensitivities.

The fuel cross-price elasticities derived from this panel data specification are also different from the earlier estimates – both in terms of signs and in terms of magnitudes. Electricity-gas and gas-other fuels are significant substitutes. Electricity and other fuels, in contrast, are complementary fuels even in the Hicksian sense, although the cross-price sensitivity between the two fuels is small. The national-level annual model, on the other hand, shows complementarity between gas and other fuels and substitutability between the other fuel pairs. Yet the national-level quarterly specification found complementarity between electricity and gas, the two main fuels, and substitutability in the other fuels.

One should, therefore, not be surprised if the DWL numbers behave very differently. In order to present an idea of their behaviour, an aggregate DWL summary across the 20 quarters of the five states is presented in Table 5.6. As speculated, the distribution of the welfare cost across the three markets differs dramatically. The combined DWL on account of the electricity and gas triangles is \$131 million, which is less than 10 per cent of the corresponding annual model estimate of \$1343 million.

Table 5.6 **The estimates of deadweight loss, panel data**

Commodities	Electricity	Gas	Other fuels	Non-fuel	Row sum
	Harberger rectangles and triangles (\$ million)				
Electricity	*48.381*	-63.292	3.694	0.000	-11.218
Gas		*82.602*	-31.766	0.000	50.835
Other fuels			*372.770*	0.000	372.770
Non-fuel				*0.000*	0.000
Column sum	48.381	19.309	344.698	0.000	*412.388*

Source: Author's estimations based on the panel data.

The other fuel triangle, on the other hand, gives a loss of \$373 million, which is 16 times larger than the corresponding annual figure of just \$23 million. Also, the rectangles are small (in absolute terms) whereas in the other two sets of estimates, the rectangles imply substantial welfare improvement/losses. For instance, a tax on other fuels in the presence of a tax on electricity and gas in the case of the annual model results in a welfare improvement of more than three-quarters of one billion dollars. The present estimates, in contrast, imply a welfare loss of less than four million dollars associated with the same tax structure.

Surprisingly, however, the overall DWL is not greatly different from the previous two estimates. Based on the panel data, the carbon tax is expected to reduce the consumer welfare in five states by \$412 million. This number increases to \$434 million if the Australian Capital Territory (ACT), the Northern Territory (NT) and Tasmania (TAS) are accounted for by applying the per capita weighted average welfare loss, based on the five states.

5.5 Summary

The AI model comprising electricity, gas, other fuels and non-fuel household consumption expenditure was re-estimated in this chapter after incorporating local curvature conditions with a view to assessing the impact of a carbon tax on welfare. The curvature restricted methodology was applied to three data sets: 1) national-level annual data from 1970 to 1998, 2) national-level quarterly data from the third quarter 1969 to the second quarter 1998, and 3) state-level quarterly data on five states spanning the period from the third quarter 1984 to the second quarter 1998.

In the case of the annual data set, the curvature restrictions were imposed at 1998 and at the fourth quarter 1997 for the corresponding quarterly specification. The underlying expenditure function for the panel data specification was restricted to be concave in prices in the neighbourhood of the fourth quarter 1997, and corresponding to Western Australia. For the annual data, the expenditure function was found to be concave over the entire sampled period, although some curvature violations were noted for the other two specifications.

In analysing the welfare implications of a carbon tax of \$300, it is assumed that the production activity is characterised by constant marginal cost conditions and therefore perfectly elastic supply curves. As a result of this full pass-through assumption, the carbon tax of \$300 is estimated to increase the price of electricity, gas and other fuels by 72 per cent, 53 per cent and 88 per cent, respectively. The carbon tax revenue is assumed to be recycled in the form of a payroll tax reduction, which leaves consumer income and non-fuel prices unaltered. The main findings of the study are summarised below:

- The annual model finds electricity-gas and electricity-other fuels to be substitutes, while gas and other fuels are complements.
- The national-level quarterly specification, in contrast, shows complementarity between electricity and gas. The other fuel pairs, electricity-gas and gas-other fuels, are substitutes.
- The fuel cross-price elasticities for the panel data are typically very small (in absolute terms) in relation to the corresponding national-level estimates. However, the cross-price elasticity between electricity and other fuels is negative, whereas the other cross-price sensitivities are positive.
- The demand for other fuels is found to be the most (own) price responsive across the three data sets. This is followed by electricity in the two annual data specifications and by gas in the state-level model.

- Gas demand is found to be particularly price responsive in Victoria, where the gas demand elasticity is estimated to vary between -0.73 and -0.80.
- The carbon tax is expected to result in a deadweight loss of \$495 million, roughly 7 per cent of total household fuel expenditure in the case of annual data. This loss figure falls slightly to \$482 million for the quarterly data and to \$434 million for the panel data model.

Notes

[1] For a comprehensive assessment of socioeconomic impacts of climate change, see IPCC (1996), Chapter 6.

[2] The elements of the SM for the last sampled year in the case of the annual data and the last four quarters for the quarterly data are used to estimate the DWL.

[3] The assumption of horizontal supply conditions is invoked for the sake of convenience. However, given the fact that the welfare analysis in this chapter deals with the long-run, the assumption of constant returns to scale is not entirely inappropriate.

[4] Common and Hamilton (1996) and McDougall and Dixon (1996), using large-scale economic models, found that carbon tax recycling in the form of a payroll tax deduction may even slightly increase incomes and reduce general prices. However, for the sake of simplicity these favourable effects are ignored.

[5] A more general review is given in the introductory chapter.

[6] For some recent developments on energy-climate issues, see McKibbin *et al.* (1999). For a survey article on the estimation of the deadweight loss, see Hines Jr. (1999).

[7] Recently Cornwell and Creedy (1997a) have combined their work on environmental taxes in Australia.

[8] The trend variable is not considered in this set of applications largely because the respective coefficients were mostly insignificant in the corresponding applications in Chapter 3.

[9] The elements of the Slutsky matrix are the second-order partial derivatives of the expenditure function with respect to the commodity prices i.e., $S_{ij} = \partial^2 e / \partial p_i \partial p_j$. Alternatively, the SM elements can be viewed as the first derivatives of the Hicksian demand functions.

[10] For a detailed treatment of the (local) concavity procedure, see Chapter 6, Section 6.2.

[11] For a brief description of the three data sets, see Chapter 3, Section 3.3.

[12] The DWL rectangles and triangles are also popularly known as Harberger rectangles and triangles.

[13] This tax rate roughly corresponds to a tax rate of US$200 per tonne of carbon, in 1992 dollars, as analysed by Brown *et al.* (1999) to assess the impact of the Kyoto protocol on various regions including Australia.

[14] Information on CO_2 factors and actual CO_2 emissions was obtained from the NGGIC (1999). The power generation data was obtained from Bush *et al.* (1999).

[15] See, for example, Common and Hamilton (1996) and McDougall and Dixon (1996).

[16] The demand functions remain downward sloping over the entire sample range even when the curvature restrictions are not incorporated in estimation.

[17] The real expenditure on gas and other fuels in the fourth quarter 1989 fell by 47 per cent and 37 per cent, respectively, as compared with the previous quarter. The electricity consumption fell relatively mildly, by 13.7 per cent.

Appendix Table A5.1 **New South Wales: third quarter, 1997**

Commodities	Electricity	Gas	Other fuels	Non-fuel	Row sum
	Harberger rectangles and triangles ($ million)				
Electricity	4.953	-3.321	0.151	0.000	1.782
Gas		3.832	-1.518	0.000	2.315
Other fuels			18.008	0.000	18.008
Non-fuel				0.000	0.000
Column sum	4.953	0.512	16.641	0.000	22.105
	Slutsky matrix ($)				
Electricity	-3.020	1.380	-0.037	1.457	na
Gas	1.380	-4.343	0.514	3.175	na
Other fuels	-0.037	0.514	-7.292	6.800	na
Non-fuel	1.457	3.175	6.800	-12.044	na
Eigenvalues	1.8E-15	-3.5E+00	-5.8E+00	-1.7E+01	na
	Marshallian elasticities*				
Electricity	-0.242	0.122	-0.005	-0.422	0.547
Gas	0.636	-2.549	0.258	-0.888	2.543
Other fuels	-0.059	0.403	-4.959	3.035	1.580
Non-fuel	-0.016	0.002	0.008	-0.996	1.002
	Hicksian elasticities				
Electricity	-0.232	0.123	-0.004	0.113	0.000
Gas	0.681	-2.541	0.263	1.597	0.000
Other fuels	-0.031	0.408	-4.956	4.579	0.000
Non-fuel	0.002	0.005	0.010	-0.017	0.000

Note: *- The last column in this panel presents income elasticities and not the row sum.
Source: Author's estimations based on the panel data.

Appendix Table A5.2 **New South Wales: fourth quarter, 1997**

Commodities	Electricity	Gas	Other fuels	Non-fuel	Row sum
	Harberger rectangles and triangles ($ million)				
Electricity	0.732	-3.460	0.243	0.000	-2.485
Gas	0.000	2.993	-1.600	0.000	1.393
Other fuels	0.000	0.000	16.576	0.000	16.576
Non-fuel				0.000	0.000
Column sum	0.732	-0.467	15.218	0.000	15.483
	Slutsky matrix ($)				
Electricity	-0.447	1.438	-0.060	-1.169	na
Gas	1.438	-3.391	0.542	1.968	na
Other fuels	-0.060	0.542	-6.712	6.190	na
Non-fuel	-1.169	1.968	6.190	-7.361	na
Eigenvalues	2.6E-01	-1.4E-14	-4.7E+00	-1.3E+01	na
	Marshallian elasticities*				
Electricity	-0.042	0.153	-0.007	-0.530	0.426
Gas	1.997	-5.811	0.808	-2.797	5.803
Other fuels	-0.164	1.170	-12.447	8.763	2.678
Non-fuel	-0.016	0.002	0.008	-0.996	1.002
	Hicksian elasticities				
Electricity	-0.036	0.153	-0.006	-0.110	0.000
Gas	2.078	-5.805	0.812	2.915	0.000
Other fuels	-0.127	1.173	-12.445	11.399	0.000
Non-fuel	-0.002	0.003	0.008	-0.010	0.000

Note: *- The last column in this panel presents income elasticities and not the row sum.
Source: Author's estimations based on the panel data.

Appendix Table A5.3 **New South Wales: first quarter, 1998**

Commodities	Electricity	Gas	Other fuels	Non-fuel	Row sum
	Harberger rectangles and triangles ($ million)				
Electricity	1.486	-3.189	0.228	0.000	-1.475
Gas		2.441	-1.478	0.000	0.964
Other fuels			15.012	0.000	15.012
Non-fuel				0.000	0.000
Column sum	1.486	-0.748	13.762	0.000	14.501
	Slutsky matrix ($)				
Electricity	-0.906	1.325	-0.057	-0.577	na
Gas	1.325	-2.767	0.501	1.384	na
Other fuels	-0.057	0.501	-6.079	5.559	na
Non-fuel	-0.577	1.384	5.559	-6.591	na
Eigenvalues	3.9E-15	-4.0E-01	-4.0E+00	-1.2E+01	na
	Marshallian elasticities*				
Electricity	-0.088	0.145	-0.007	-0.504	0.454
Gas	6.443	-16.535	2.614	-9.042	16.519
Other fuels	-0.222	1.575	-16.392	11.783	3.256
Non-fuel	-0.016	0.002	0.008	-0.996	1.002
	Hicksian elasticities				
Electricity	-0.082	0.145	-0.006	-0.057	0.000
Gas	6.685	-16.529	2.623	7.222	0.000
Other fuels	-0.174	1.576	-16.390	14.989	0.000
Non-fuel	-0.001	0.002	0.008	-0.010	0.000

Note: *- The last column in this panel presents income elasticities and not the row sum.
Source: Author's estimations based on the panel data.

Appendix Table A5.4 **New South Wales: second quarter, 1998**

Commodities	Electricity	Gas	Other fuels	Non-fuel	Row sum
	Harberger rectangles and triangles ($ million)				
Electricity	1.268	-3.310	0.190	0.000	-1.851
Gas		3.025	-1.531	0.000	1.494
Other fuels			17.515	0.000	17.515
Non-fuel				0.000	0.000
Column sum	1.268	-0.285	16.174	0.000	17.157
	Slutsky matrix ($)				
Electricity	-0.773	1.376	-0.047	-0.772	na
Gas	1.376	-3.428	0.519	2.071	na
Other fuels	-0.047	0.519	-7.092	6.483	na
Non-fuel	-0.772	2.071	6.483	-8.049	na
Eigenvalues	-4.7E-15	-3.3E-01	-4.8E+00	-1.4E+01	na
	Marshallian elasticities*				
Electricity	-0.074	0.148	-0.006	-0.513	0.445
Gas	1.475	-4.557	0.594	-2.061	4.550
Other fuels	-0.072	0.512	-6.014	3.839	1.735
Non-fuel	-0.016	0.002	0.008	-0.996	1.002
	Hicksian elasticities				
Electricity	-0.068	0.148	-0.005	-0.075	0.000
Gas	1.540	-4.551	0.601	2.409	0.000
Other fuels	-0.047	0.514	-6.011	5.544	0.000
Non-fuel	-0.001	0.003	0.009	-0.011	0.000

Note: *- The last column in this panel presents income elasticities and not the row sum.
Source: Author's estimations based on the panel data.

Appendix Table A5.5 **Victoria: third quarter, 1997**

Commodities	Electricity	Gas	Other fuels	Non-fuel	Row sum
	Harberger rectangles and triangles ($ million)				
Electricity	3.721	-2.776	0.069	0.000	1.014
Gas		6.421	-1.585	0.000	4.835
Other fuels			23.569	0.000	23.569
Non-fuel				0.000	0.000
Column sum	3.721	3.645	22.053	0.000	29.419
	Slutsky matrix ($)				
Electricity	-3.092	1.572	-0.023	1.760	na
Gas	1.572	-9.915	0.732	9.743	na
Other fuels	-0.023	0.732	-13.007	11.433	na
Non-fuel	1.760	9.743	11.433	-25.021	na
Eigenvalues	-1.6E-14	-4.2E+00	-1.2E+01	-3.5E+01	na
	Marshallian elasticities*				
Electricity	-0.254	0.123	-0.004	-0.419	0.554
Gas	0.193	-1.473	0.077	-0.265	1.468
Other fuels	-0.034	0.228	-3.260	1.735	1.331
Non-fuel	-0.016	0.002	0.008	-0.996	1.002
	Hicksian elasticities				
Electricity	-0.244	0.129	-0.002	0.117	0.000
Gas	0.219	-1.458	0.083	1.156	0.000
Other fuels	-0.010	0.242	-3.256	3.024	0.000
Non-fuel	0.002	0.013	0.011	-0.026	0.000

Note: *- The last column in this panel presents income elasticities and not the row sum.
Source: Author's estimations based on the panel data.

Appendix Table A5.6 **Victoria: fourth quarter, 1997**

Commodities	Electricity	Gas	Other fuels	Non-fuel	Row sum
	Harberger rectangles and triangles ($ million)				
Electricity	0.672	-2.876	0.167	0.000	-2.037
Gas		5.925	-1.662	0.000	4.262
Other fuels			22.425	0.000	22.425
Non-fuel				0.000	0.000
Column sum	0.672	3.049	20.930	0.000	24.651
	Slutsky matrix ($)				
Electricity	-0.559	1.629	-0.056	-1.292	na
Gas	1.629	-9.150	0.767	8.623	na
Other fuels	-0.056	0.767	-12.375	10.713	na
Non-fuel	-1.292	8.623	10.713	-19.125	na
Eigenvalues	-5.4E-15	-4.3E-01	-1.1E+01	-2.9E+01	na
	Marshallian elasticities*				
Electricity	-0.055	0.155	-0.006	-0.528	0.434
Gas	0.244	-1.593	0.098	-0.337	1.587
Other fuels	-0.052	0.366	-4.618	2.774	1.530
Non-fuel	-0.016	0.002	0.008	-0.996	1.002
	Hicksian elasticities				
Electricity	-0.049	0.158	-0.005	-0.104	0.000
Gas	0.267	-1.579	0.102	1.211	0.000
Other fuels	-0.030	0.379	-4.614	4.266	0.000
Non-fuel	-0.002	0.010	0.010	-0.019	0.000

Note: *- The last column in this panel presents income elasticities and not the row sum.
Source: Author's estimations based on the panel data.

Appendix Table A5.7 **Victoria: first quarter, 1998**

Commodities	Electricity	Gas	Other fuels	Non-fuel	Row sum
	Harberger rectangles and triangles ($ million)				
Electricity	1.325	-2.595	0.150	0.000	-1.120
Gas		5.023	-1.491	0.000	3.532
Other fuels			19.782	0.000	19.782
Non-fuel				0.000	0.000
Column sum	1.325	2.427	18.442	0.000	22.194
	Slutsky matrix ($)				
Electricity	-1.101	1.470	-0.051	-0.458	na
Gas	1.470	-7.756	0.688	7.139	na
Other fuels	-0.051	0.688	-10.917	9.414	na
Non-fuel	-0.458	7.139	9.414	-17.010	na
Eigenvalues	-8.9E-15	-1.3E+00	-9.9E+00	-2.6E+01	na
	Marshallian elasticities*				
Electricity	-0.112	0.145	-0.006	-0.496	0.468
Gas	0.270	-1.656	0.109	-0.373	1.651
Other fuels	-0.058	0.402	-4.972	3.046	1.582
Non-fuel	-0.016	0.002	0.008	-0.996	1.002
	Hicksian elasticities				
Electricity	-0.105	0.149	-0.005	-0.039	0.000
Gas	0.295	-1.644	0.112	1.237	0.000
Other fuels	-0.034	0.414	-4.969	4.589	0.000
Non-fuel	-0.001	0.010	0.010	-0.019	0.000

Note: *- The last column in this panel presents income elasticities and not the row sum.
Source: Author's estimations based on the panel data.

Appendix Table A5.8 **Victoria: second quarter, 1998**

Commodities	Electricity	Gas	Other fuels	Non-fuel	Row sum
	Harberger rectangles and triangles ($ million)				
Electricity	1.090	-2.745	0.118	0.000	-1.537
Gas		5.772	-1.591	0.000	4.181
Other fuels			23.091	0.000	23.091
Non-fuel				0.000	0.000
Column sum	1.090	3.027	21.617	0.000	25.734
	Slutsky matrix ($)				
Electricity	-0.906	1.555	-0.040	-0.799	na
Gas	1.555	-8.913	0.734	8.377	na
Other fuels	-0.040	0.734	-12.743	11.002	na
Non-fuel	-0.799	8.377	11.002	-19.524	na
Eigenvalues	-1.8E-14	-1.0E+00	-1.1E+01	-3.0E+01	na
	Marshallian elasticities*				
Electricity	-0.090	0.149	-0.005	-0.509	0.455
Gas	0.234	-1.569	0.093	-0.322	1.563
Other fuels	-0.037	0.259	-3.565	1.967	1.376
Non-fuel	-0.016	0.002	0.008	-0.996	1.002
	Hicksian elasticities				
Electricity	-0.083	0.153	-0.004	-0.066	0.000
Gas	0.257	-1.555	0.098	1.200	0.000
Other fuels	-0.017	0.271	-3.560	3.306	0.000
Non-fuel	-0.001	0.011	0.011	-0.021	0.000

Note: *- The last column in this panel presents income elasticities and not the row sum.
Source: Author's estimations based on the panel data.

Appendix Table A5.9 **Queensland: third quarter, 1997**

Commodities	Electricity	Gas	Other fuels	Non-fuel	Row sum
	Harberger rectangles and triangles ($ million)				
Electricity	5.438	-3.555	0.183	0.000	2.067
Gas		3.936	-1.627	0.000	2.309
Other fuels			17.492	0.000	17.492
Non-fuel				0.000	0.000
Column sum	5.438	0.381	16.049	0.000	21.868
	Slutsky matrix ($)				
Electricity	-6.075	2.707	-0.083	2.969	na
Gas	2.707	-8.172	1.009	4.991	na
Other fuels	-0.083	1.009	-12.978	11.458	na
Non-fuel	2.969	4.991	11.458	-18.953	na
Eigenvalues	-5.3E-15	-6.9E+00	-1.1E+01	-2.9E+01	na
	Marshallian elasticities*				
Electricity	-0.255	0.119	-0.005	-0.414	0.554
Gas	0.854	-3.080	0.347	-1.194	3.073
Other fuels	-0.070	0.482	-5.724	3.621	1.692
Non-fuel	-0.016	0.002	0.008	-0.996	1.002
	Hicksian elasticities				
Electricity	-0.245	0.120	-0.004	0.128	0.000
Gas	0.909	-3.072	0.352	1.811	0.000
Other fuels	-0.040	0.486	-5.721	5.276	0.000
Non-fuel	0.002	0.004	0.009	-0.016	0.000

Note: *- The last column in this panel presents income elasticities and not the row sum.
Source: Author's estimations based on the panel data.

Appendix Table A5.10 **Queensland: fourth quarter, 1997**

Commodities	Electricity	Gas	Other fuels	Non-fuel	Row sum
	Harberger rectangles and triangles ($ million)				
Electricity	1.049	-3.697	0.281	0.000	-2.367
Gas		2.898	-1.731	0.000	1.167
Other fuels			16.436	0.000	16.436
Non-fuel				0.000	0.000
Column sum	1.049	-0.799	14.986	0.000	15.236
	Slutsky matrix ($)				
Electricity	-1.172	2.816	-0.128	-1.724	na
Gas	2.816	-6.018	1.075	2.637	na
Other fuels	-0.128	1.075	-12.195	10.515	na
Non-fuel	-1.724	2.637	10.515	-11.074	na
Eigenvalues	2.3E-01	-2.1E-14	-8.4E+00	-2.2E+01	na
	Marshallian elasticities*				
Electricity	-0.060	0.149	-0.007	-0.520	0.437
Gas	11.213	-28.001	4.548	-15.738	27.978
Other fuels	-0.310	2.208	-22.575	16.515	4.162
Non-fuel	-0.015	0.002	0.008	-0.996	1.002
	Hicksian elasticities				
Electricity	-0.053	0.149	-0.007	-0.089	0.000
Gas	11.609	-27.996	4.559	11.828	0.000
Other fuels	-0.251	2.208	-22.573	20.616	0.000
Non-fuel	-0.001	0.002	0.008	-0.009	0.000

Note: *- The last column in this panel presents income elasticities and not the row sum.
Source: Author's estimations based on the panel data.

Appendix Table A5.11 **Queensland: first quarter, 1998**

Commodities	Electricity	Gas	Other fuels	Non-fuel	Row sum
	Harberger rectangles and triangles ($ million)				
Electricity	1.881	-3.378	0.265	0.000	-1.232
Gas		2.269	-1.599	0.000	0.670
Other fuels			14.960	0.000	14.960
Non-fuel				0.000	0.000
Column sum	1.881	-1.109	13.627	0.000	14.398
	Slutsky matrix ($)				
Electricity	-2.101	2.573	-0.121	-0.608	na
Gas	2.573	-4.711	0.992	1.578	na
Other fuels	-0.121	0.992	-11.100	9.429	na
Non-fuel	-0.608	1.578	9.429	-9.864	na
Eigenvalues	-3.3E-14	-9.7E-01	-6.9E+00	-2.0E+01	na
	Marshallian elasticities*				
Electricity	-0.108	0.141	-0.007	-0.492	0.466
Gas	-3.597	7.673	-1.464	5.060	-7.672
Other fuels	-0.646	4.573	-45.644	34.173	7.544
Non-fuel	-0.015	0.002	0.008	-0.996	1.002
	Hicksian elasticities				
Electricity	-0.101	0.141	-0.006	-0.033	0.000
Gas	-3.712	7.677	-1.465	-2.500	0.000
Other fuels	-0.533	4.569	-45.642	41.607	0.000
Non-fuel	-0.001	0.001	0.008	-0.009	0.000

Note: *- The last column in this panel presents income elasticities and not the row sum.
Source: Author's estimations based on the panel data.

Appendix Table A5.12 **Queensland: second quarter, 1998**

Commodities	Electricity	Gas	Other fuels	Non-fuel	Row sum
			Harberger rectangles and triangles ($ million)		
Electricity	1.502	-3.627	0.225	0.000	-1.901
Gas		3.156	-1.676	0.000	1.480
Other fuels			17.203	0.000	17.203
Non-fuel				0.000	0.000
Column sum	1.502	-0.471	15.752	0.000	16.782
			Slutsky matrix ($)		
Electricity	-1.677	2.762	-0.102	-1.164	na
Gas	2.762	-6.553	1.040	3.136	na
Other fuels	-0.102	1.040	-12.764	11.091	na
Non-fuel	-1.164	3.136	11.091	-12.591	na
Eigenvalues	-1.0E-14	-7.4E-01	-8.9E+00	-2.4E+01	na
			Marshallian elasticities*		
Electricity	-0.085	0.146	-0.006	-0.506	0.452
Gas	2.986	-8.202	1.206	-4.182	8.192
Other fuels	-0.090	0.635	-7.208	4.753	1.910
Non-fuel	-0.016	0.002	0.008	-0.996	1.002
			Hicksian elasticities		
Electricity	-0.078	0.146	-0.006	-0.062	0.000
Gas	3.106	-8.196	1.217	3.874	0.000
Other fuels	-0.062	0.636	-7.206	6.632	0.000
Non-fuel	-0.001	0.003	0.009	-0.011	0.000

Note: *- The last column in this panel presents income elasticities and not the row sum.
Source: Author's estimations based on the panel data.

Appendix Table A5.13 **South Australia: third quarter, 1997**

Commodities	Electricity	Gas	Other fuels	Non-fuel	Row sum
	Harberger rectangles and triangles ($ million)				
Electricity	5.994	-2.632	0.089	0.000	3.450
Gas		4.106	-1.452	0.000	2.654
Other fuels			22.001	0.000	22.001
Non-fuel				0.000	0.000
Column sum	5.994	1.474	20.638	0.000	28.106
	Slutsky matrix ($)				
Electricity	-15.582	4.664	-0.094	11.036	na
Gas	4.664	-19.840	2.097	17.365	na
Other fuels	-0.094	2.097	-37.985	31.996	na
Non-fuel	11.036	17.365	31.996	-62.048	na
Eigenvalues	1.1E-14	-2.0E+01	-2.8E+01	-8.8E+01	na
	Marshallian elasticities*				
Electricity	-0.336	0.107	-0.004	-0.371	0.604
Gas	0.337	-1.829	0.136	-0.468	1.824
Other fuels	-0.037	0.247	-3.435	1.868	1.357
Non-fuel	-0.016	0.002	0.008	-0.996	1.002
	Hicksian elasticities				
Electricity	-0.324	0.111	-0.002	0.215	0.000
Gas	0.374	-1.818	0.143	1.302	0.000
Other fuels	-0.010	0.255	-3.430	3.185	0.000
Non-fuel	0.004	0.008	0.011	-0.023	0.000

Note: *- The last column in this panel presents income elasticities and not the row sum.
Source: Author's estimations based on the panel data.

Appendix Table A5.14 **South Australia: fourth quarter, 1997**

Commodities	Electricity	Gas	Other fuels	Non-fuel	Row sum
	Harberger rectangles and triangles ($ million)				
Electricity	2.856	-2.747	0.195	0.000	0.304
Gas		3.558	-1.542	0.000	2.016
Other fuels			21.002	0.000	21.002
Non-fuel				0.000	0.000
Column sum	2.856	0.811	19.655	0.000	23.321
	Slutsky matrix ($)				
Electricity	-7.423	4.868	-0.207	2.175	na
Gas	4.868	-17.191	2.227	13.737	na
Other fuels	-0.207	2.227	-36.259	30.189	na
Non-fuel	2.175	13.737	30.189	-46.258	na
Eigenvalues	-9.7E-15	-9.2E+00	-2.5E+01	-7.3E+01	na
	Marshallian elasticities*				
Electricity	-0.186	0.131	-0.005	-0.453	0.513
Gas	0.528	-2.282	0.213	-0.735	2.277
Other fuels	-0.060	0.413	-5.059	3.111	1.595
Non-fuel	-0.016	0.002	0.008	-0.996	1.002
	Hicksian elasticities				
Electricity	-0.178	0.133	-0.004	0.049	0.000
Gas	0.565	-2.274	0.218	1.491	0.000
Other fuels	-0.033	0.419	-5.056	4.670	0.000
Non-fuel	0.001	0.006	0.010	-0.016	0.000

Note: *- The last column in this panel presents income elasticities and not the row sum.
Source: Author's estimations based on the panel data.

Appendix Table A5.15 **South Australia: first quarter, 1998**

Commodities	Electricity	Gas	Other fuels	Non-fuel	Row sum
	Harberger rectangles and triangles ($ million)				
Electricity	3.281	-2.527	0.183	0.000	0.936
Gas		3.009	-1.417	0.000	1.592
Other fuels			19.078	0.000	19.078
Non-fuel				0.000	0.000
Column sum	3.281	0.482	17.844	0.000	21.607
	Slutsky matrix ($)				
Electricity	-8.529	4.479	-0.193	3.782	na
Gas	4.479	-14.540	2.047	11.100	na
Other fuels	-0.193	2.047	-32.939	27.318	na
Non-fuel	3.782	11.100	27.318	-42.079	na
Eigenvalues	-7.1E-23	-1.1E+01	-2.1E+01	-6.6E+01	na
	Marshallian elasticities*				
Electricity	-0.220	0.125	-0.005	-0.434	0.533
Gas	0.646	-2.570	0.261	-0.901	2.564
Other fuels	-0.066	0.451	-5.431	3.396	1.649
Non-fuel	-0.016	0.002	0.008	-0.996	1.002
	Hicksian elasticities				
Electricity	-0.211	0.127	-0.004	0.088	0.000
Gas	0.689	-2.562	0.266	1.607	0.000
Other fuels	-0.037	0.457	-5.428	5.009	0.000
Non-fuel	0.002	0.005	0.009	-0.016	0.000

Note: *- The last column in this panel presents income elasticities and not the row sum.
Source: Author's estimations based on the panel data.

Appendix Table A5.16 **South Australia: second quarter, 1998**

Commodities	Electricity	Gas	Other fuels	Non-fuel	Row sum
	Harberger rectangles and triangles ($ million)				
Electricity	3.135	-2.660	0.141	0.000	0.616
Gas		3.590	-1.491	0.000	2.099
Other fuels			22.034	0.000	22.034
Non-fuel				0.000	0.000
Column sum	3.135	0.930	20.684	0.000	24.749
	Slutsky matrix ($)				
Electricity	-8.148	4.713	-0.150	3.048	na
Gas	4.713	-17.346	2.153	14.032	na
Other fuels	-0.150	2.153	-38.041	31.570	na
Non-fuel	3.048	14.032	31.570	-48.376	na
Eigenvalues	-9.2E-15	-1.0E+01	-2.5E+01	-7.7E+01	na
	Marshallian elasticities*				
Electricity	-0.206	0.128	-0.005	-0.443	0.525
Gas	0.475	-2.155	0.191	-0.660	2.150
Other fuels	-0.041	0.281	-3.764	2.119	1.405
Non-fuel	-0.016	0.002	0.008	-0.996	1.002
	Hicksian elasticities				
Electricity	-0.197	0.130	-0.003	0.070	0.000
Gas	0.511	-2.146	0.197	1.438	0.000
Other fuels	-0.017	0.287	-3.760	3.490	0.000
Non-fuel	0.001	0.006	0.011	-0.018	0.000

Note: *- The last column in this panel presents income elasticities and not the row sum.
Source: Author's estimations based on the panel data.

Appendix Table A5.17 **Western Australia: third quarter, 1997**

Commodities	Electricity	Gas	Other fuels	Non-fuel	Row sum
	Harberger rectangles and triangles ($ million)				
Electricity	4.603	-3.568	0.150	0.000	1.185
Gas		6.110	-1.671	0.000	4.439
Other fuels			17.532	0.000	17.532
Non-fuel				0.000	0.000
Column sum	4.603	2.542	16.011	0.000	23.156
	Slutsky matrix ($)				
Electricity	-9.751	5.152	-0.130	4.738	na
Gas	5.152	-24.058	1.967	17.011	na
Other fuels	-0.130	1.967	-24.667	22.876	na
Non-fuel	4.738	17.011	22.876	-44.754	na
Eigenvalues	-7.5E-14	-1.2E+01	-2.7E+01	-6.4E+01	na
	Marshallian elasticities*				
Electricity	-0.246	0.122	-0.005	-0.421	0.549
Gas	0.372	-1.908	0.150	-0.517	1.903
Other fuels	-0.049	0.336	-4.309	2.538	1.485
Non-fuel	-0.016	0.002	0.008	-0.996	1.002
	Hicksian elasticities				
Electricity	-0.236	0.125	-0.003	0.115	0.000
Gas	0.406	-1.898	0.155	1.337	0.000
Other fuels	-0.023	0.344	-4.306	3.985	0.000
Non-fuel	0.002	0.007	0.010	-0.020	0.000

Note: *- The last column in this panel presents income elasticities and not the row sum.
Source: Author's estimations based on the panel data.

Appendix Table A5.18 **Western Australia: fourth quarter, 1997**

Commodities	Electricity	Gas	Other fuels	Non-fuel	Row sum
	Harberger rectangles and triangles ($ million)				
Electricity	0.667	-3.726	0.243	0.000	-2.817
Gas		5.204	-1.767	0.000	3.437
Other fuels			16.354	0.000	16.354
Non-fuel				0.000	0.000
Column sum	0.667	1.478	14.830	0.000	16.975
	Slutsky matrix ($)				
Electricity	-1.413	5.381	-0.209	-3.759	na
Gas	5.381	-20.492	2.079	13.031	na
Other fuels	-0.209	2.079	-23.010	21.140	na
Non-fuel	-3.759	13.031	21.140	-30.413	na
Eigenvalues	7.5E-03	-4.8E-14	-2.4E+01	-5.1E+01	na
	Marshallian elasticities*				
Electricity	-0.047	0.153	-0.007	-0.529	0.429
Gas	0.617	-2.489	0.249	-0.860	2.483
Other fuels	-0.104	0.739	-8.258	5.559	2.064
Non-fuel	-0.016	0.002	0.008	-0.996	1.002
	Hicksian elasticities				
Electricity	-0.041	0.155	-0.006	-0.108	0.000
Gas	0.652	-2.481	0.252	1.578	0.000
Other fuels	-0.075	0.746	-8.255	7.584	0.000
Non-fuel	-0.002	0.005	0.009	-0.012	0.000

Note: *- The last column in this panel presents income elasticities and not the row sum.
Source: Author's estimations based on the panel data.

Appendix Table A5.19 **Western Australia: first quarter, 1998**

Commodities	Electricity	Gas	Other fuels	Non-fuel	Row sum
	Harberger rectangles and triangles ($ million)				
Electricity	1.535	-3.353	0.230	0.000	-1.587
Gas		4.207	-1.641	0.000	2.566
Other fuels			15.360	0.000	15.360
Non-fuel				0.000	0.000
Column sum	1.535	0.853	13.950	0.000	16.339
	Slutsky matrix ($)				
Electricity	-3.252	4.842	-0.199	-1.404	na
Gas	4.842	-16.563	1.931	9.849	na
Other fuels	-0.199	1.931	-21.612	19.116	na
Non-fuel	-1.404	9.849	19.116	-26.870	na
Eigenvalues	1.7E-14	-2.8E+00	-2.0E+01	-4.5E+01	na
	Marshallian elasticities*				
Electricity	-0.104	0.144	-0.006	-0.497	0.463
Gas	0.825	-2.995	0.334	-1.153	2.989
Other fuels	-0.132	0.932	-10.144	7.003	2.340
Non-fuel	-0.016	0.002	0.008	-0.996	1.002
	Hicksian elasticities				
Electricity	-0.097	0.145	-0.006	-0.042	0.000
Gas	0.870	-2.988	0.337	1.781	0.000
Other fuels	-0.097	0.938	-10.141	9.301	0.000
Non-fuel	-0.001	0.004	0.008	-0.012	0.000

Note: *- The last column in this panel presents income elasticities and not the row sum.
Source: Author's estimations based on the panel data.

Appendix Table A5.20 **Western Australia: second quarter, 1998**

Commodities	Electricity	Gas	Other fuels	Non-fuel	Row sum
	Harberger rectangles and triangles ($ million)				
Electricity	1.193	-3.549	0.193	0.000	-2.163
Gas		5.126	-1.696	0.000	3.430
Other fuels			17.341	0.000	17.341
Non-fuel				0.000	0.000
Column sum	1.193	1.577	15.838	0.000	18.608
	Slutsky matrix ($)				
Electricity	-2.528	5.126	-0.167	-2.415	na
Gas	5.126	-20.185	1.996	12.966	na
Other fuels	-0.167	1.996	-24.400	22.099	na
Non-fuel	-2.415	12.966	22.099	-32.108	na
Eigenvalues	-2.6E-14	-1.8E+00	-2.4E+01	-5.3E+01	na
	Marshallian elasticities*				
Electricity	-0.080	0.148	-0.006	-0.511	0.449
Gas	0.559	-2.352	0.225	-0.778	2.346
Other fuels	-0.058	0.408	-5.010	3.072	1.588
Non-fuel	-0.016	0.002	0.008	-0.996	1.002
	Hicksian elasticities				
Electricity	-0.073	0.150	-0.005	-0.071	0.000
Gas	0.593	-2.344	0.230	1.521	0.000
Other fuels	-0.035	0.414	-5.007	4.628	0.000
Non-fuel	-0.001	0.006	0.010	-0.014	0.000

Note: *- The last column in this panel presents income elasticities and not the row sum.
Source: Author's estimations based on the panel data.

6

Inter-fuel substitution in the industrial and commercial sectors

Synopsis

Using national-level annual data this chapter models the inter-fuel substitution structure of the Australian commercial and industrial sectors by dividing the two sectors into 37 industries and categorising energy employed into electricity, gas, oil and coal. Owing to the non-availability of adequate data on the level of output, capital stock and some other factor inputs, the production structure of an industry is assumed to be weakly separable in capital, labour, materials and energy aggregates, which, in turn, are assumed to be homothetic, linearly homogenous, in their components. The resulting unit energy cost function to the optimising agent is represented by a translog specification. In addition to the relative fuel prices, a trend variable is included in the set of regressors with a view to capturing the fuel efficiency biases, if any, of changing technology. Local curvature conditions are imposed on the underlying cost function due to the frequent concavity violations. Serial correlation, another problem encountered at the estimation stage, is not addressed as the model could not be medicated for the autocorrelated errors given the concavity treatment.

Technical progress has been electricity using but oil saving in almost all industries. The direction of bias in the other two fuels is less obvious although, on average, it is positive for gas and negative for coal. Electricity demand is relatively insensitive to own-price variations, whereas the demand for the other three fuels is considerably sensitive, especially that of oil. While there is some evidence of complementarity in fuel use, especially in the case of coal-oil and coal-electricity pairs, in most of the industries substitutability is the dominant feature. Gas demand is particularly sensitive to petroleum prices, which lends support to the generally held notion that gas share in Australia has increased at the expense of oil.

6.1 Introduction

The last three chapters dealt with the issue of consumer energy demand, including its econometric estimation and economic applications. Chapter 3, the first in this category, modelled the structure of consumer energy demand by parameterising the Almost Ideal (AI) demand system as an autoregressive error model and a vector error correction model. In order to examine the robustness of the inter-fuel relationships, the next chapter employed dynamic single equation methods to estimate the interrelated consumer energy demands. The chapter also included the projections of energy demand and associated CO_2 emissions under business-as-usual conditions and a carbon tax scenario. The last chapter, Chapter 5, was devoted to analysing the impact of the carbon tax on welfare; the deadweight loss of the tax was computed using alternative estimates of residential energy demand.

However, the residential sector accounts for less than one-tenth of gross national energy consumption, the industrial and commercial sectors consuming the rest. Given the overwhelming significance of the industrial and commercial sectors on account of energy consumption, it is crucial to analyse the energy demand structure in the two sectors. From the policy point of view – not only the environmental policy but also the competition policy – knowledge of the inter-fuel substitution elasticities is of crucial significance. The inter-fuel substitution patterns are expected to be different in different industries, depending on the nature of individual industries. It is, therefore, important to investigate such patterns at the level of individual industries, depending on the availability of the relevant data.

This study investigates the inter-fuel substitution opportunities in the industrial and commercial sectors by dividing the two sectors into 37 sub-sectors – the maximum possible detail permitted by the data – and categorising energy use into electricity, gas, oil and coal. The fuel structure in each industry is modelled using the translog factor demand system. The resulting energy demand system is estimated for each industry using national-level annual time series data spanning the period from 1974 to 1995.

The rest of the chapter is organised as follows. Section 6.2 presents the model specification and derives fuel share equations of the translog factor demand system and discusses some of the methodological and econometric issues. A brief description of the data used in this study is given in Section 6.3. Results are reported and briefly discussed in the next section. Finally, Section 6.5 summarises the study and offers some concluding remarks.

6.2 Model

It is assumed that the production structure of the ith industry is characterised by a production function that is twice differentiable, monotonic and quasi-concave. The production function in its general form is written as:

$$Q = Q(K, L, E, M, t) \tag{6-1}$$

where Q stands for the level of output, K for capital stock, L for labour, E for energy, M for material inputs including intermediate inputs and raw materials and t is time. It is assumed that the above production function is weakly separable in its factor aggregates. In the context of the aggregate energy input (E), for instance, this assumption implies that the marginal rates of substitution between any two energy sources are independent of the quantities of capital, labour and materials. This restriction on the production structure is expressed by writing the production function in (6-1) as:

$$Q = f(K, L, e(E_1, E_2, \ldots\ldots, E_n, t), M, t) \tag{6-2}$$

where e is an aggregator function and E_i are individual fuels. The aggregator function is assumed to be homothetic in its components. This assumption of homotheticity permits an investigation of the inter-fuel substitution structure separately as the first stage of a two-stage optimisation procedure. Denny and Fuss (1977) have shown that homotheticity is a necessary and sufficient condition for the validity of a two-stage optimisation process. In the first stage the optimal fuel mix is obtained and in the second stage optimal quantities of capital, labour, material inputs and aggregate energy are chosen given the optimal fuel mix.

Assuming that factor prices and output are exogenously-determined, and invoking the duality theory of production and cost, the production technology in (6-2) can be uniquely represented by a cost function that is also weakly separable. The corresponding cost function takes the form:

$$C = C(p_K, p_L, p_M, P_e(p_{e1}, p_{e2}, \ldots\ldots, p_{en}, t), Q, t) \tag{6-3}$$

where P_e is an aggregator function that aggregates the individual energy prices, p_{ei}s, leading to an aggregate energy price index. Unlike the overall cost function, the energy price aggregator function which, appropriately, is known as unit energy cost to the optimising agent, does not include an output variable, total energy in this case, owing to the assumption of homotheticity.

As the objective of this chapter is to investigate only the inter-fuel substitution possibilities in various industries, the development of the second stage (the aggregate model) is ignored and attention is focussed on developing the inter-fuel substitution model.[1] The unit energy cost function is represented by a linearly homogenous (in aggregate energy) translog cost function of the form:[2]

$$\log P_e = \log(\gamma_0) + \sum_i \gamma_i \log p_{ei} + 1/2 \sum_i \sum_j \gamma_{ij} \log p_{ei} \log p_{ej} + \sum_i \gamma_{it} p_{ei} t \tag{6-4}$$

where log stands for natural logarithm and γ_0, γ_is, γ_{ij}s and γ_{it}s are the unknown population parameters to be estimated. Differentiating the above cost function logarithmically and employing Shepherd's lemma gives the following system of cost shares:

$$w_i = \gamma_i + \sum_j \gamma_{ij} \log p_{ej} + \lambda_i t \tag{6-5}$$

where w_i is the share of the ith fuel in total energy cost and γ_i and γ_{ij} are the parameters as defined previously. For this system to be well behaved, it must satisfy the adding-up, linear homogeneity, and symmetry properties. These conditions imply the following set of restrictions on the model parameters:

$$\begin{aligned} &\sum_i \gamma_i = 1 \\ &\sum_i \gamma_{ij} = \sum_j \gamma_{ij} = 0 \\ &\gamma_{ij} = \gamma_{ji}, \qquad i \neq j \\ &\sum_i \gamma_{it} = 0 \end{aligned} \tag{6-6}$$

The above set of restrictions, which hold globally, can easily be imposed. The concavity property also requires restrictions on parameters. For this property to hold, the matrix of second order partial derivatives with respect to prices is required to be negative semidefinite.[3] In order to arrive at an expression for this matrix, the cost function is logarithmically differentiated twice to obtain:

$$\frac{\partial \log P_e}{\partial \log p_{ei} \partial \log p_{ej}} = \frac{\delta_{ij} p_{ei} \partial P_e / \partial p_{ei}}{P_e} - \frac{p_{ei} (\partial P_e / \partial p_{ei}) p_{ej} (\partial P_e / \partial p_{ej})}{P_e^2} + \frac{p_{ei} p_{ej} \, {}^{\partial^2 P_e} \!\big/\! {}_{\partial p_{ei} \partial p_{ej}}}{p_e} . \tag{6-7}$$

The above expression is simplified, utilizing Shepherd's lemma and because the left-hand-side of the above equation equals γ_{ij}, to:

$$\gamma_{ij} = \delta_{ij} w_i - w_i w_j + \frac{p_{ei} p_{ej}}{p_e} \frac{\partial^2 P_e}{\partial p_{ei} \partial p_{ej}} \tag{6-8}$$

By rearranging, the following expression is obtained:

$$\frac{\partial^2 P_e}{\partial p_{ei} p_{ej}} = \theta_{ij} = \frac{P_e}{p_{ei} p_{ej}} \left[\gamma_{ij} + w_i w_j - \delta_{ij} w_i \right] \tag{6-9}$$

Note that the matrix $[w_i w_j - \delta_{ij} w_i]$ is negative semidefinite as long as the estimated shares are non-negative. Thus, the negative semidefiniteness of the substitution matrix in (6-9) is ensured if matrix $A = [\gamma_{ij}]$ is negative semidefinite provided the estimated shares are non-negative. The A matrix can be made negative semidefinite by reparameterising as:

$$A = -B'B \tag{6-10}$$

where B is an upper-triangular matrix. In the case of $n=4$, the matrix will take the form:

$$B = \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ 0 & b_{22} & b_{23} \\ 0 & 0 & b_{33} \end{bmatrix} \tag{6-11}$$

However, as discussed in Diewert and Wales (1987), this reparametrisation imposes too much of a curvature and leads, in an extreme situation, to a complete loss of flexibility, that is, a situation where a translog specification reduces to its special case of a Cobb-Douglas specification. An alternative procedure proposed initially by Lau (1978) for production functions and recently by Moschini (1998) in the context of the semiflexible Almost Ideal (AI) demand system and by Ryan and Wales (1998, 1999, 2000) for both commodity and factor demand systems, tries to impose concavity at a point rather than the global one as discussed above. This method of local concavity is used here because the flexibility of the cost function is maintained despite the regularity conditions. Also, the local conditions lead to an estimated cost function that is generally concave and not just at the point of restrictions (Ryan and Wales 2000:256-7).

Without loss of generality, the point $p_i = 1$ is chosen to be the one where concavity conditions are imposed. As a result the substitution matrix becomes:[4]

$$\theta_{ij} = \gamma_{ij} + \gamma_i \gamma_j - \delta_{ij} \gamma_i \tag{6-12}$$

In order for $w_i = \gamma_i$ in Equation (6-12), it is also necessary that t assumes a value of zero at the chosen reference point. To obtain this result, the trend variable, t, following Ryan and Wales (2000: 254-5), is defined as follows: $t = \bar{t} - t^*$ where $\bar{t}$ is time trend and t^* is the chosen reference point. The authors argue that the likelihood value and elasticities are not affected by introducing time trend in this fashion.

The local curvature conditions are imposed by way of setting θ_{ij} to $-(B'B)_{ij}$. Thus, in the estimation the $[\gamma_{ij}]$ matrix is replaced by -[$(B'B)_{ij} + \gamma_i \gamma_j - \delta_{ij} \gamma_i$]. This will ensure concavity at the point $p_i = 1$ as the two matrices are negative semidefinite, assuming that the estimates of γ_is are non-negative. The estimates of γ_is can be restricted to be non-negative by replacing γ_i by $\gamma_i^* \gamma_i^*$ in the estimation procedure.

The empirical results presented in Section 4.2 incorporate local concavity restrictions as, in earlier applications, the translog fuel choice model frequently violated curvature property; indeed, the own-price elasticities were positive in many instances. However, it (curvature violation) was not the only problem encountered at the estimation stage. Autocorrelated structure was another significant problem as a typical DW was less than unity.

Initially, both concavity and a simple autocorrelation treatment – a diagonal autocovariance matrix and, therefore, the same autocorrelation coefficient across all equations – were implemented. However, the resulting elasticities were either implausibly very large or small (in absolute terms). The bizarre outcome is possibly because a relatively short time-series of 22-data points is not rich enough to estimate both short and long-run structures. At the same time the autocorrelation treatment was not very effective in the sense that many DWs were still small. A non-diagonal R was not considered due to the small number of observations.

The problem of autocorrelation, therefore, is not addressed because the presence of serial correlation means a relatively greater scatter around the unknown true population parameters but the estimated parameters are still unbiased.[5] However, concavity violations are not acceptable as such violations typically imply, in the present case, positive own-price elasticities. Indeed, in this case, the unconstrained estimates of elasticities were positive in a significant number of cases. The results that are reported in Section 6.4 are concavity constrained. The local concavity restrictions are imposed at the last sampled year, 1995.

Thus, the following system of four equations (symmetry imposed) for each of the 37 industries is estimated:

$$\begin{aligned} w_1 &= \gamma_1 + \gamma_{11}\log p_{e1} + \gamma_{12}\log p_{e2} + \gamma_{13}\log p_{e3} + \gamma_{14}\log p_{e4} + \gamma_{1t}t + u_1 \\ w_2 &= \gamma_2 + \gamma_{12}\log p_{e1} + \gamma_{22}\log p_{e2} + \gamma_{23}\log p_{e3} + \gamma_{24}\log p_{e4} + \gamma_{2t}t + u_2 \\ w_3 &= \gamma_3 + \gamma_{13}\log p_{e1} + \gamma_{23}\log p_{e2} + \gamma_{33}\log p_{e3} + \gamma_{34}\log p_{e4} + \gamma_{3t}t + u_3 \\ w_4 &= \gamma_4 + \gamma_{14}\log p_{e1} + \gamma_{24}\log p_{e2} + \gamma_{34}\log p_{e3} + \gamma_{44}\log p_{e4} + \gamma_{4t}t + u_4 \end{aligned} \qquad (6\text{-}21)$$

where 1 = electricity; 2 = gas; 3 = oil; 4 = coal; and u_i are assumed to be independently and identically distributed random errors. Technical change is ith fuel using (saving) if γ_{it} is positive (negative). It is said to be neutral if γ_{it} is zero. For the purposes of estimating the share system, the coal share equation is arbitrarily dropped and the remaining three equations are estimated simultaneously in SHAZAM using the non-linear seemingly unrelated regression procedure. All parameters of the deleted equation are recovered with the help of demand system restrictions.

The elasticities of substitution in the case of the translog model are computed from:

$$\sigma_{ii} = \frac{\gamma_{ii} + w_i^2 - w_i}{w_i^2}, \quad i = 1,2,3,4 \tag{6-13}$$

$$\sigma_{ij} = \frac{\gamma_{ij} + w_i w_j}{w_i w_j}, \quad i, j = 1,2,3,4; \quad i \neq j \tag{6-14}$$

The price elasticities of demand are calculated from:

$$\varepsilon_{ii} = w_i \sigma_{ii} = \frac{\gamma_{ii} + w_i^2 - w_i}{w_i}, \quad i = 1,2,3,4 \tag{6-15}$$

$$\varepsilon_{ij} = w_j \sigma_{ij} = \frac{\gamma_{ij} + w_i w_j}{w_i}, \quad i, j = 1,2,3,4; \quad i \neq j \tag{6-16}$$

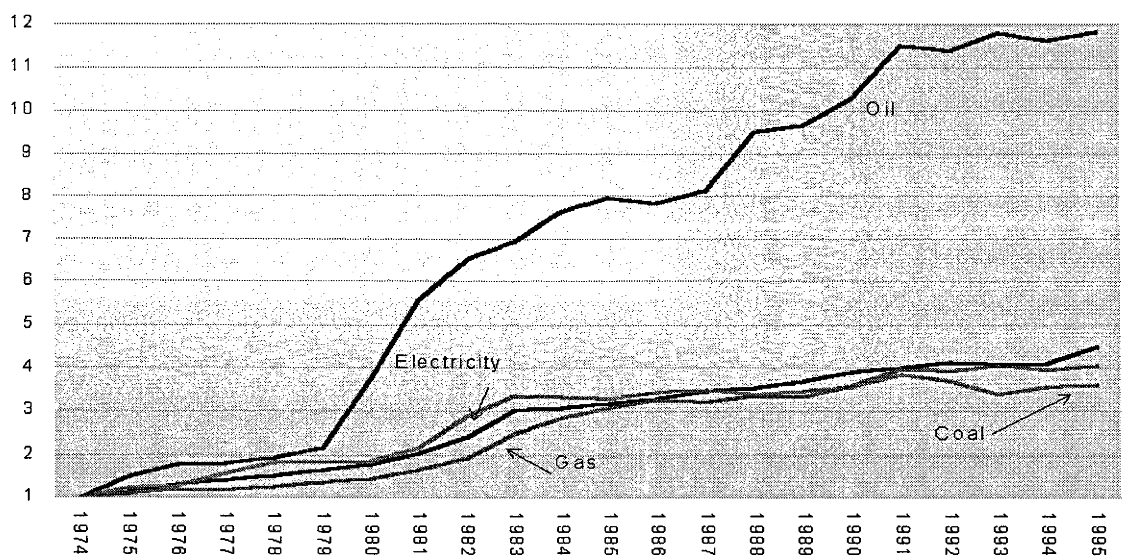
6.3 Data

The study uses national-level annual data spanning the period from 1974 to 1995, that is, 22 data points. 1974 is the earliest year for which detailed energy consumption data are available. The quantity data on different fuels are largely taken from 'Australian Energy: Market Developments and Projections to 2014-15' published by the Australian Bureau of Agricultural and Resource Economics (Bush *et al.* 1999). The publication provides a detailed picture of the energy situation in Australia. As far as energy consumption across various industries/sectors is concerned, it contains energy use data by fuel type at roughly the two-digit level industrial classification,[6] although the fuel consumption data for the period 1996 to 1998 are available but with much less detail as far as industrial coverage is concerned. That three-year period, therefore, is not included in this analysis. For the purposes of this study, total energy use by an industry is divided into the use of electricity, gas, and oil and coal. The non-residential sector in this respect is divided into 37 sub-sectors (Chapter 2, Table 2.2), depending on the availability of energy data.

The price data are taken primarily from the Australian Gas Association (AGA 1994) and O'Dwyer and Hu (1998). The Australian Gas Association provides historical prices of heating oil, automotive diesel oil (ADO), industrial diesel fuel (IDF), fuel oil (FO), black coal, brown coal, brown coal briquettes, coke, gas and electricity for the period 1974 to 1993. There are separate electricity and gas price series for industrial and commercial users. The other fuel prices are not differentiated. These price series are updated using data from the Electricity Supply Association of Australia (ESAA) (ESAA 1999) and AGA (1998). O'Dwyer and Hu (1998) provide national-level prices for electricity, gas, petrol and ADO for the period 1970 to 1996. Again, from this source, separate prices are available for industrial and commercial users but no distinction is made as far as petrol and ADO prices are concerned. As is obvious from the above discussion, price information is not available for all fuel categories. In order to price those fuels, a weighted average price based on the remaining fuels in that group is used in this study.

The price indices of the four fuels are plotted in Figure 6.1 for the period 1974 to 1995.[7] The electricity and gas price indices correspond to the industrial users. The commercial sector price indices of the two fuels are not plotted here as they are not markedly different from their industrial sector counterparts. The price of petroleum products (oil) rose over this period of 22 years by a factor of 12. It is worth noting that most of this petroleum price inflation, nearly 80 per cent, occurred between 1979 and 1991, triggered by the second oil shock that hit the economy during 1980.

Figure 6.1 **Fuel price indices**



Sources: Australian Gas Association, 1994. *Gas Statistics Australia 1998*, Canberra; O' Dwyer, T. & Hu, B., 1998. 'Long term energy price trends', *National Economic Review*, 41:13-8.

Prices of the other three fuels, in contrast, were not greatly affected by the oil shock and shared a common inflationary pattern over this period. The nominal price of these fuels increased by a factor of around four, leading to a substantial reduction in the prices of these fuels relative to that of petroleum products. Owing to the very similar inflationary pattern that these fuels shared, there is not much (relative) price variation within this group. This could mean a multicollinearity problem, leading to unreliable estimates of the demand parameters and thus elasticities.

6.4 Results

The estimation results are summarised in Table 6.1. The first two columns respectively report the proportion of the regression coefficients and elasticities, Allen-Uzawa elasticities of substitution and price elasticities of demand, which are statistically significant (the findings in this section should, however, be taken with caution because of the serial correlation problem). The last four columns contain coefficients of the trend variable in individual equations. The system or generalised R^2 ($\widetilde{R}^2$) and individual R^2s are not presented in this table primarily because of space constraints. The generalised R^2 across industries is, however, very high, almost unity, implying that the null hypotheses of slope coefficients in all equations simultaneously being zero is rejected very easily.[8] The individual R^2, in contrast, varies substantially both within and across industries, ranging from 0.20 to 0.99. However, the individual R^2 is a flawed measure of the goodness of fit as, in the simultaneous equation context, the generalised R^2 rather than the individual ones is maximised (Berndt 1991:468).

On average, nearly three-quarters of the regression parameters are significantly estimated. However, this proportion varies greatly across industries/sectors. In agriculture, forestry and fishing and finance, insurance, property and business sectors, all estimated parameters are significant. In some other cases almost half of the coefficients are not precisely estimated. Included in this group are other manufacturing, glass and glass products and other metals product industries. In most of the industries – 25 – the proportion of significant coefficients exceeds 70 per cent.

The overall proportion of significant elasticities, in contrast, is relatively small: 63 per cent. Again, this rate is quite variable across industries, ranging, this time, from 0 to 100 per cent. A cursory look at the first two columns gives the impression that the two rates are not quite related to each other, although the significance rate of elasticities is expected to be an increasing function of the significance rate of parameters. Indeed, the first impression is quite correct, surprisingly though, as the degree of linear association between the two variables is quite small: less than 0.03.

The trend coefficients are presented in the last four columns of the table. A positive (negative) trend variable coefficient in the ith fuel share equation implies that technical change is the ith fuel using (saving). A zero coefficient, in contrast, implies that technical change is unbiased. The technical change that took place during the 22-year period or so significantly enhanced electricity consumption, as in 28 out of 37 industries the coefficient of the trend variable is statistically positive. It is only in two industries –

private electricity generation and accommodation, cultural and personal – that technical change has been electricity saving.

Table 6.1 **Estimation results, a summary**

Industries/Sectors	Proportion of significant		Technical bias			
	Para-meters	Elasti-cities	Electri-city	Gas	Oil	Coal
Agriculture, forestry and fishing	100	0	+ve	..	-ve	..
Mining	89	48	0.0	+ve	-ve	-ve
Food, beverages and tobacco						
Meat and meat products	67	88	+ve	+ve	-ve	0
Dairy products	94	72	+ve	+ve	-ve	+ve
Fruit and vegetable processing	72	44	+ve	0	-ve	+ve
Oil and fat	78	100	+ve	0	0	0
Flour and cereal products	61	68	0	0	0	+ve
Bakery products	75	87	+ve	+ve	-ve	..
Other food manufacturing	50	48	+ve	0	0	0
Beverage and malt products	72	68	+ve	0	-ve	-ve
Tobacco products	89	72	+ve	+ve	-ve	-ve
Textile, clothing, footwear and leather	67	56	+ve	0	-ve	-ve
Wood, paper and printing	83	68	+ve	0	-ve	-ve
Petroleum, coal and chemicals						
Petroleum refining	75	80	+ve	0	-ve	..
Petroleum and coal products nec	58	80	+ve	+ve	-ve	..
Basic chemicals	89	48	+ve	0	-ve	-ve
Other chemicals, rubber and plastic	72	76	+ve	-ve	0	-ve
Non-metallic mineral products						
Glass and glass products	50	80	+ve	0	0	..
Ceramics	72	68	+ve	0	-ve	0
Cement, lime, plaster and concrete	89	68	+ve	-ve	0	-ve
Non-metallic mineral products nec	50	32	0	0	-ve	0
Metal products						
Iron and steel	72	28	+ve	+ve	-ve	-ve
Basic non-ferrous metals	83	72	+ve	+ve	-ve	-ve
Other metal products	42	100	+ve	0	0	..
Machinery and equipment	75	53	+ve	-ve	0	..
Electricity, gas and water						
Public electricity generation	61	32	0	+ve	-ve	+ve
Private electricity generation	89	56	-ve	+ve	-ve	-ve
Gas production and distribution	75	67	0	+ve	-ve	..
Water, sewerage and drainage	75	87	+ve	+ve	-ve	..
Construction	75	67	0	+ve	0	..
Wholesale and retail trade	67	67	+ve	0	-ve	..
Transport and storage	86	68	0	0	0	0
Communication	75	67	+ve	+ve	-ve	..
Finance, insurance, property and business	100	100	+ve	-ve		..
Government administration and defense	67	8	+ve	0	-ve	-ve
Education, health and community services	67	24	+ve	+ve	-ve	-ve
Accommodation, cultural and personal	94	92	-ve	+ve	-ve	-ve
All Sectors	73	63	..	..	..	..

Note: 1. nec = not elsewhere specified. 2. -ve = negative, +ve = positive.
Source: Author's estimations.

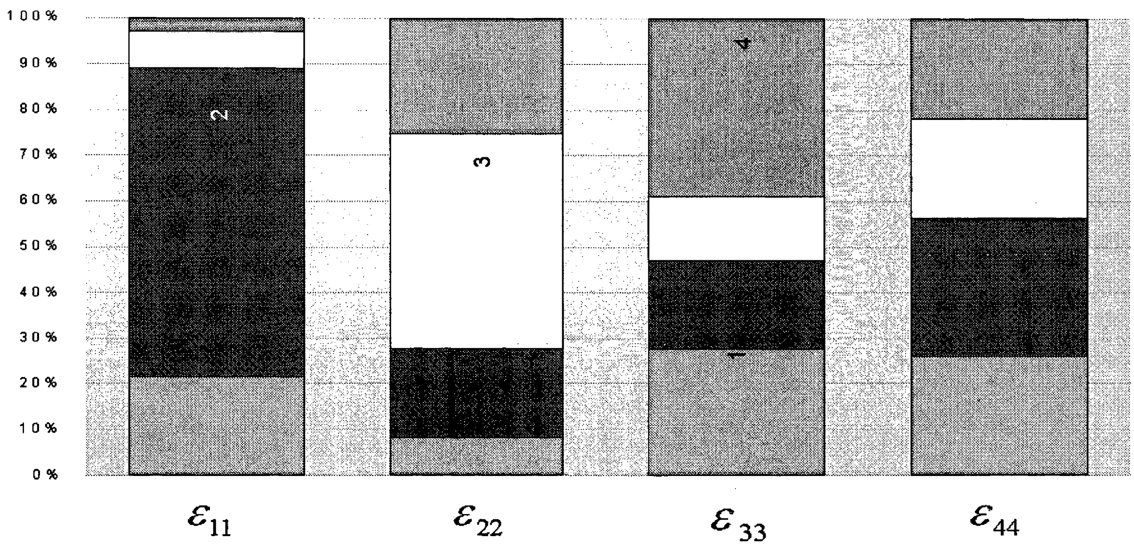
The case of oil is roughly opposite. Here, technical progress led to a reduction in the consumption of oil in 26 industries. In the remaining industries the coefficient of the trend variable is insignificant. As far as gas demand is concerned, technical progress has enhanced the consumption of this fuel in many industries but this incidence of a positive bias is lower than that in the case of electricity; the coefficient of the trend variable is positive in 16 industries. Four industries observed gas saving technical change. The impact of technical progress on gas use in the remaining 15 industries is uncertain as the respective coefficients are not significant.

Many industries have observed savings in coal use on account of technical change. Included in this group of industries are mining, textiles, iron and steel and some service sector industries. Also in this group of industries is the private power generation sector, which seems to be a good sign. However, the private sector's share in total power generation is no more than 10 per cent. In contrast, coal use in the public electricity generation industry, which relies heavily on coal for its energy needs, has increased on account of technical change.

Own-price elasticities of the four fuels are summarised in Figure 6.2 and reported along with the approximate t-scores in the Appendix Tables A6.1 to A6.4. For the purpose of this graph, the values of an elasticity across industries are divided into four brackets. A fairly liberal procedure is adopted in this graph in treating an elasticity estimate as insignificantly different from zero. An estimated elasticity is considered as insignificant if the associated t-ratio is less or equal to one in absolute terms.[9] Despite this generosity, a large number of the estimated elasticities are not distinguishable from zero. For instance, in nearly 30 per cent of the industries the petroleum products elasticity is not significant. Further, in one-quarter of all industries the coal elasticity is not reliably estimated. This fraction reduces to a little more than 21 per cent for electricity. The proportion of insignificant elasticities is the lowest in the case of gas: approximately 8 per cent.

The demand for electricity is mostly not very price sensitive because in nearly 70 per cent of the industries the elasticity is less than 0.5 in absolute terms. It is only in the case of the construction industry that the electricity demand is price elastic. However, electricity use in the construction industry is very minor, less than 0.5 per cent of the total energy use by the industry, which may have led to this unusual result. There are two likely reasons for the fact that electricity demand is relatively price insensitive. Firstly, and more importantly, technical change has made electricity an essential fuel in almost every industry. Secondly, the price of this fuel during the past 22-year period has not changed much, especially in comparison with the price of petroleum products. Indeed, the real price of the fuel has fallen over time as the producer price index has risen by a factor of 8 over this period of about two decades.

Figure 6.2 **Own-price elasticities** (per cent distribution)



Note: 1: ε_{ii} insignificant, 2: $0<|\varepsilon_{ii}|\leq 0.50$, 3: $0.50<|\varepsilon_{ii}|\leq 1.0$, 4: $|\varepsilon_{ii}|>1.0$.
Source: Author's estimations.

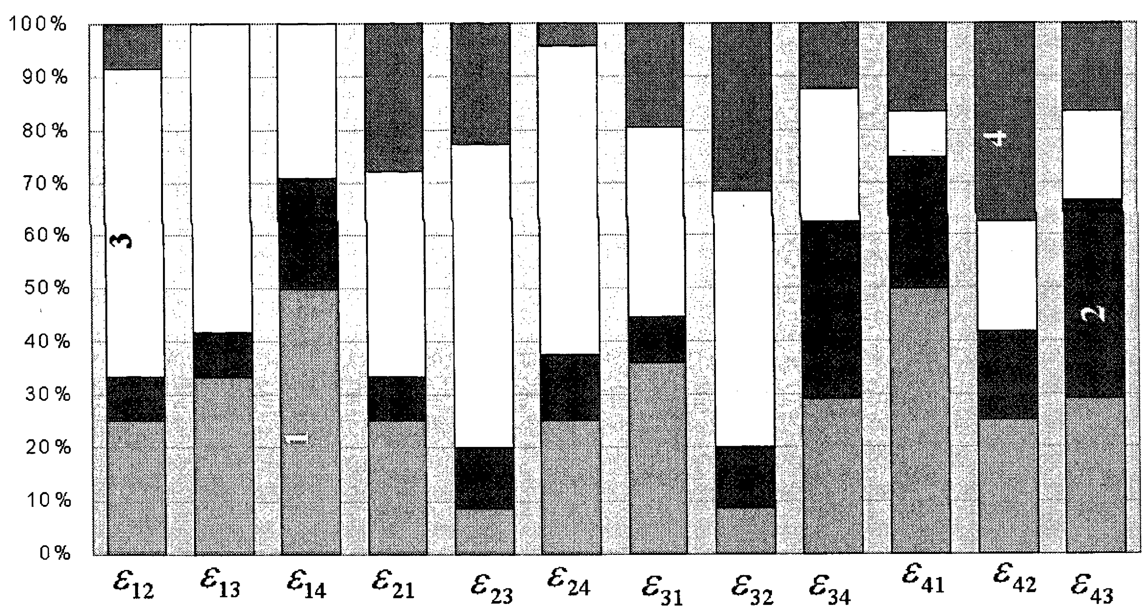
This contrasts sharply with the case of petroleum or oil elasticities. In nearly 40 per cent of the industries, demand for the fuel is elastic ($|\varepsilon_{ii}|$ > 1). Indeed, in this case technical change and the price factor have worked in exactly the opposite direction. Technical change liberated almost all industries considerably from petroleum use. Further, the price of the fuel rose by a factor of 12, which is in sharp contrast to the other fuel prices.

It seems that industries adjust their gas consumption well in response to gas price variations as the gas elasticity is greater than 0.50 for nearly three-quarters of all industries. Indeed, in the case of 25 per cent of the industries the elasticity exceeds unity. Coal demand is also reasonably sensitive to its price as in roughly 65 per cent of industries the own-price elasticity exceeds 0.5. However, coal demand is relatively less (own) price elastic compared to gas and petroleum fuels but significantly more sensitive in comparison with electricity.

The coal elasticity in public electricity generation, which overwhelmingly dominates the electricity generation sector, is not very high, -0.14, and is significant only at the 10 per cent level of significance. Conversely, coal demand in private electricity generation is considerably own-price sensitive, with an elasticity estimate of -0.69 and is highly significant. The gas demand elasticity, on the other hand, is relatively large in both sub-sectors: -0.63 for public and -0.78 for private. Also, gas is a strong substitute for coal in private electricity generation; the corresponding public sub-sector elasticity is roughly of the same magnitude but not significant (t-score = 1.65).

Gas and petroleum fuels are found to be substitutable fuels in 80 per cent of the industries (Figure 6.3). This, in combination with a substantial increase in the price of petroleum fuels relative to that of gas, largely explains a 2.5-fold increase in the share of gas in primary energy consumption between 1974 and 1998. The gas share rose from 7 per cent in 1974 to 18 per cent in 1998. Rapidly rising petroleum prices could also have led to an increase in the electricity share at the expense of a fall in the share of petroleum fuels as many industries, nearly 55 per cent, consider electricity and petroleum as substitutes. However, switching from oil to electricity is expected to be relatively minor as electricity demand is relatively less sensitive to variations in petroleum prices.

Figure 6.3 **Cross-price elasticities** (per cent distribution)



Note: 1: ε_{ij} insignificant, 2: ε_{ij} negative, 3: $0 < \varepsilon_{ij} \leq 0.50$, 4: $\varepsilon_{ij} > 0.50$, $i,j = 1,2,3,4$, $i \neq j$.
Source: Author's estimations.

Electricity and gas are consumed as substitute fuels in nearly two-thirds of the industries. However, gas demand is relatively more sensitive to electricity price variations owing to its generally smaller share in energy use. This lends some support to the idea that there may have also been some switching from electricity to gas, but this is not expected to be significant given the relatively stable prices of the two fuels.

Significant substitution possibilities are also found between gas and coal. However, substitution between electricity and coal and between coal and petroleum is not very high. For instance, significant substitution possibilities are found between electricity and coal in 25 per cent of the industries. The corresponding fraction for the coal-oil pair is roughly 35 per cent. Indeed, coal and oil are employed in a complementary fashion in 35 per cent of the industries. Included in this group of industries, among others, are mining, chemicals, basic non-ferrous metals and wood, paper and printing industries. Significant complementarity in the use of electricity and coal is also found in 20 per cent of the industries.

The cross-price elasticity between electricity and coal is not significantly estimated in almost half of the industries, which is very high in comparison to the case of the other cross-price elasticities. The incidence of insignificant cross-price elasticities, in contrast, is the lowest in the case of the gas-petroleum pair. This is followed by coal-gas and electricity-gas with an insignificance rate of 25 per cent in each case.

6.5 Summary

Using national-level annual data from 1974 to 1995, this chapter investigated Australian industrial and commercial energy demand with a view to determining the inter-fuel substitution relationships and fuel efficiency biases. To this end, the two sectors were divided into 37 industries and total energy employed by an industry into electricity, gas, oil and coal. The production structure of an industry was assumed to be weakly separable in the factor aggregates, which, in turn, were assumed to be homothetic in their components. This crucial two-step assumption helped analyse the fuel choice problem in isolation, without worrying about the aggregate choice.

The underlying unit energy cost function, represented by the translog specification, frequently violated the curvature conditions in most industries. Local as opposed to global concavity was imposed which led to a generally well behaved cost function without losing flexibility. Autocorrelation, another major problem encountered in this exercise, could not be addressed partly because of the complication caused by concavity restrictions and partly because of the small number of observations. The main findings are summarised here:

- Technical change is electricity-using but oil-saving in all industries with, however, a few exceptions. The direction of bias is less obvious in the other two fuels although, on average, it is positive for gas and negative for coal.

- Electricity demand is (own) price inelastic. In nearly half of the industries the elasticity is less than one-quarter of a point (in absolute terms). Further, in almost two-thirds of the industries it is less than one-half.
- The demand for the other three fuels, that is, gas, oil and coal, is not only more price sensitive but also the sensitivity varies greatly across industries. This is particularly true for oil, where, in nearly 40 per cent of industries the elasticity exceeds unity.
- There is some evidence of complementarity in fuel use, especially in the case of the coal-oil and coal-electricity pairs. The dominant feature characterising most industries is, however, substitutability between fuels, especially in the case of gas-oil and gas-electricity.

Notes

[1] It is desirable to model both the aggregate and inter-fuel models as this adds a tremendous amount of information. However, modelling of the second stage is not pursued here due solely to the non-availability of data on capital, output and some other variables at the level of detail needed to estimate the corresponding aggregate structure. However, in the next chapter the inter-factor choice is modelled along with the inter-fuel choice with less sectoral detail.

[2] The conditions implied by linear homogeneity are stricter than those of homotheticity (Berndt 1991:469-70). These are needed to ensure that the product of aggregate energy price and quantity equals total energy cost (Fuss 1977:91).

[3] The reparameterisation, a necessary and sufficient condition for the matrix to be negative semidefinite, is suggested by Diewert and Wales (1987).

[4] It is assumed that γ_0 takes the value of one or, in other words, a normalised version of the unit cost function is assumed.

[5] Implicit in this statement is the assumption that the relationship is not spurious, that is, that there is cointegration.

[6] The transport sector is covered at the two-digit level industrial classification, the manufacturing sector mostly at the three-digit level, and the power generation sector is covered at the three to four digit-level industrial classification. The coverage of the remaining sectors including agriculture is usually at the division level.

[7] For a brief discussion on the energy consumption patterns in the 37 industries, see Chapter 2, Section 2.4.

[8] However, this result should be taken cautiously, as the value of this goodness of fit statistic is typically very high.

[9] In the discussion that follows elasticities are interpreted in absolute terms.

Appendix Table A6.1 **Price elasticities for electricity demand, 1995**

Sub-sectors	ε_{11}		ε_{12}		ε_{13}		ε_{14}	
	Value	*t-score*	Value	*t-score*	Value	*t-score*	Value	*t-score*
Agriculture, forestry and fishing	0.000	*0.00*	..	..	0.000	*0.00*	..	..
Mining	-0.002	*0.14*	-0.017	*0.47*	0.017	*0.39*	0.001	*0.40*
Meat and meat products	-0.149	*2.49*	0.078	*1.95*	0.121	*2.06*	-0.050	*4.05*
Dairy products	-0.054	*1.40*	-0.060	*4.64*	0.096	*1.89*	0.019	*1.96*
Fruit and vegetable processing	-0.006	*0.40*	-0.038	*1.03*	0.021	*0.44*	0.023	*0.56*
Oil and fat products	-0.470	*4.00*	0.451	*4.03*	0.174	*2.82*	-0.155	*5.73*
Flour mill and cereal food products	-0.017	*1.16*	-0.035	*1.42*	0.059	*1.93*	-0.006	*0.21*
Bakery products	-0.189	*2.92*	0.254	*4.45*	-0.065	*3.05*	..	..
Other food products	-0.110	*0.82*	0.015	*0.23*	0.133	*2.91*	-0.038	*0.34*
Beverages and malt	-0.181	*2.31*	0.142	*2.79*	-0.001	*0.02*	0.040	*1.01*
Tobacco products	-0.093	*1.24*	0.053	*1.09*	-0.061	*2.22*	0.101	*2.67*
Textile, clothing, footwear and leather	-0.085	*0.87*	0.080	*1.06*	0.011	*0.32*	-0.006	*0.49*
Wood, paper products + Printing, publishing and recorded media	-0.106	*1.65*	0.102	*1.97*	0.010	*0.50*	-0.006	*0.23*
Petroleum refining	-0.449	*1.91*	-0.002	*0.01*	0.451	*5.45*	..	..
Petroleum and coal products nec	-0.759	*3.77*	0.268	*1.61*	0.490	*6.93*	..	..
Basic chemical products	0.000	*0.01*	0.020	*0.46*	-0.018	*0.41*	-0.001	*0.43*
Other chemical products + rubber & plastic products	-0.492	*5.08*	0.122	*1.49*	0.324	*7.27*	0.046	*3.51*
Glass and glass products	-0.568	*4.11*	0.509	*4.30*	0.059	*1.07*	..	..
Ceramic products	-0.357	*4.12*	0.453	*5.98*	-0.036	*0.95*	-0.060	*2.13*
Cement, lime, plaster and concrete products	-0.277	*2.56*	0.105	*1.63*	0.127	*5.54*	0.045	*0.66*
Non-metallic mineral products nec	-0.441	*1.91*	0.280	*1.61*	0.114	*1.49*	0.047	*0.31*
Iron and steel	-0.010	*0.28*	0.045	*0.87*	-0.019	*0.85*	-0.015	*0.60*
Basic non-ferrous metals	-0.292	*2.93*	0.137	*1.90*	0.077	*2.28*	0.078	*2.37*
Other metal products	-0.297	*4.96*	0.171	*3.54*	0.126	*2.81*	..	..
Machinery and equipment	-0.072	*1.64*	-0.014	*0.57*	0.085	*2.05*	..	..
Public electricity generation	-0.161	*1.75*	0.079	*1.07*	0.010	*0.36*	0.073	*1.20*
Private electricity generation	-0.328	*1.82*	1.105	*4.14*	0.013	*0.07*	-0.790	*3.52*
Gas production and distribution	-0.650	*1.56*	0.190	*0.54*	0.459	*2.16*	..	..
Water, sewerage and drainage	-0.082	*6.34*	0.004	*4.70*	0.078	*6.19*	..	..
Construction	-1.134	*3.14*	1.330	*4.83*	-0.197	*1.28*	..	..
Wholesale and retail trade	-0.079	*1.89*	-0.008	*0.34*	0.088	*3.85*	..	..
Transport and storage	-0.230	*1.63*	0.178	*1.20*	0.156	*2.23*	-0.104	*3.96*
Communication	-0.040	*2.50*	0.029	*3.22*	0.011	*1.44*	..	..
Finance, insurance, property and business	-0.011	*3.72*	0.011	*3.72*	..	..	..	..
Government administration and defence	-0.005	*0.17*	0.007	*0.30*	-0.002	*0.26*	0.000	*0.35*
Education, health and community services	-0.116	*2.43*	0.121	*4.11*	-0.008	*0.45*	0.003	*0.52*
Accommodation, cultural and personal	-0.107	*19.48*	0.094	*18.28*	0.011	*3.57*	0.002	*5.92*

Note: 1. nec = not elsewhere classified. 2. Critical values: 10 per cent = 1.67, 5 per cent = 2.00, 1 per cent = 2.66.

Source: Author's estimations.

Appendix Table A6.2 **Price elasticities for gas demand, 1995**

Sub-sectors	ε_{21}		ε_{22}		ε_{23}		ε_{24}	
	Value	*t-score*	Value	*t-score*	Value	*t-score*	Value	*t-score*
Agriculture, forestry and fishing	..	..	..	..	..	..	..	..
Mining	-0.026	*0.47*	-0.224	*4.37*	0.232	*4.51*	0.018	*1.86*
Meat and meat products	0.294	*1.95*	-0.787	*5.97*	0.159	*1.84*	0.334	*6.52*
Dairy products	-0.120	*4.64*	-0.132	*3.27*	0.211	*4.13*	0.041	*1.32*
Fruit and vegetable processing	-0.123	*1.03*	-0.958	*4.95*	0.792	*5.71*	0.289	*2.03*
Oil and fat products	1.445	*4.03*	-2.552	*6.45*	0.615	*4.32*	0.493	*4.95*
Flour mill and cereal food products	-0.137	*1.42*	-0.676	*4.73*	0.428	*6.86*	0.385	*4.07*
Bakery products	0.495	*4.45*	-0.665	*7.79*	0.170	*2.83*	..	..
Other food products	0.052	*0.23*	-1.018	*7.84*	0.421	*5.07*	0.545	*2.71*
Beverages and malt	0.263	*2.79*	-0.562	*6.55*	0.338	*4.34*	-0.039	*0.90*
Tobacco products	0.098	*1.09*	-0.403	*4.93*	0.165	*2.22*	0.140	*3.38*
Textile, clothing, footwear and leather	0.332	*1.06*	-0.926	*3.68*	0.438	*4.82*	0.157	*4.59*
Wood, paper products + Printing, publishing and recorded media	0.440	*1.97*	-0.999	*4.94*	0.210	*3.17*	0.349	*3.78*
Petroleum refining	-0.004	*0.01*	-1.590	*5.16*	1.594	*9.78*	..	..
Petroleum and coal products nec	0.318	*1.61*	-1.271	*3.62*	0.954	*2.65*	..	..
Basic chemical products	0.015	*0.46*	-0.784	*11.86*	0.719	*9.03*	0.050	*8.30*
Other chemical products + Rubber & plastic products	0.505	*1.49*	-1.256	*4.14*	0.739	*6.38*	0.012	*0.34*
Glass and glass products	0.259	*4.30*	-0.615	*5.85*	0.357	*3.40*	..	..
Ceramic products	0.268	*5.98*	-0.677	*7.18*	0.370	*4.18*	0.039	*2.12*
Cement, lime, plaster and concrete products	0.122	*1.63*	-0.311	*3.96*	0.318	*4.77*	-0.129	*2.59*
Non-metallic mineral products nec	0.445	*1.61*	-1.078	*3.00*	0.663	*4.20*	-0.030	*0.15*
Iron and steel	0.134	*0.87*	-0.728	*4.41*	0.480	*4.13*	0.114	*0.60*
Basic non-ferrous metals	0.554	*1.90*	-0.259	*1.36*	-0.147	*2.71*	-0.148	*1.54*
Other metal products	0.603	*3.54*	-0.972	*6.72*	0.369	*3.16*	..	..
Machinery and equipment	-0.079	*0.57*	-0.181	*1.60*	0.260	*3.06*	..	..
Public electricity generation	0.185	*1.07*	-0.634	*2.46*	0.062	*0.55*	0.387	*1.65*
Private electricity generation	0.144	*4.14*	-0.783	*6.64*	0.220	*1.60*	0.419	*5.30*
Gas production and distribution	0.002	*0.54*	-0.465	*4.10*	0.463	*4.02*	..	..
Water, sewerage and drainage	0.230	*4.70*	-0.011	*0.34*	-0.219	*4.23*	..	..
Construction	2.193	*4.83*	-2.573	*9.18*	0.380	*1.85*	..	..
Wholesale and retail trade	-0.082	*0.34*	-0.122	*0.82*	0.204	*2.01*	..	..
Transport and storage	0.716	*1.20*	-2.477	*4.09*	1.559	*14.55*	0.202	*1.39*
Communication	1.187	*3.22*	-0.868	*4.18*	-0.319	*1.79*	..	..
Finance, insurance, property and business	0.615	*3.72*	-0.615	*3.72*	..	..	..	..
Government administration and defence	0.153	*0.30*	-0.215	*0.72*	0.074	*0.35*	-0.013	*0.83*
Education, health and community services	0.703	*4.11*	-0.764	*7.87*	0.074	*0.91*	-0.013	*0.73*
Accommodation, cultural and personal	1.187	*18.28*	-1.093	*15.15*	-0.071	*2.65*	-0.023	*6.32*

Note: 1. nec = not elsewhere classified. 2. Critical values: 10 per cent = 1.67, 5 per cent = 2.00, 1 per cent = 2.66.

Source: Author's estimations.

Appendix Table A6.3 **Price elasticities for oil demand, 1995**

Sub-sectors	ε_{31}		ε_{32}		ε_{33}		ε_{34}	
	Value	*t-score*	Value	*t-score*	Value	*t-score*	Value	*t-score*
Agriculture, forestry and fishing	0.000	*0.00*	..	..	0.000	*0.00*	..	..
Mining	0.018	*0.39*	0.156	*4.51*	-0.161	*2.25*	-0.013	*1.89*
Meat and meat products	0.373	*2.06*	0.130	*1.84*	-0.508	*2.04*	0.004	*0.11*
Dairy products	0.202	*1.89*	0.223	*4.13*	-0.356	*2.09*	-0.069	*1.94*
Fruit and vegetable processing	0.038	*0.44*	0.440	*5.71*	-0.529	*3.25*	0.052	*1.35*
Oil and fat products	28.104	*2.82*	30.989	*4.32*	-67.511	*6.07*	8.418	*2.88*
Flour mill and cereal food products	0.194	*1.93*	0.365	*6.86*	-0.674	*5.86*	0.115	*2.50*
Bakery products	-0.342	*3.05*	0.460	*2.83*	-0.117	*0.59*	..	..
Other food products	0.458	*2.91*	0.426	*5.07*	-1.411	*3.81*	0.527	*1.46*
Beverages and malt	-0.007	*0.02*	2.154	*4.34*	-2.660	*3.06*	0.513	*3.18*
Tobacco products	-0.988	*2.22*	1.445	*2.22*	-0.900	*0.79*	0.443	*2.09*
Textile, clothing, footwear and leather	0.118	*0.32*	1.094	*4.82*	-1.126	*3.21*	-0.085	*2.59*
Wood, paper products + Printing, publishing and recorded media	0.093	*0.50*	0.461	*3.17*	-0.249	*1.44*	-0.306	*4.80*
Petroleum refining	0.031	*5.45*	0.058	*9.78*	-0.090	*10.31*	..	..
Petroleum and coal products nec	0.111	*6.93*	0.182	*2.65*	-0.293	*3.80*	..	..
Basic chemical products	-0.002	*0.41*	0.090	*9.03*	-0.082	*6.24*	-0.006	*9.55*
Other chemical products + rubber & plastic products	1.058	*7.27*	0.583	*6.38*	-1.617	*8.83*	-0.024	*2.15*
Glass and glass products	0.428	*1.07*	5.138	*3.40*	-5.566	*3.24*	..	..
Ceramic products	-0.181	*0.95*	3.154	*4.18*	-2.994	*3.67*	0.021	*0.22*
Cement, lime, plaster and concrete products	0.281	*5.54*	0.601	*4.77*	-1.126	*6.78*	0.245	*3.28*
Non-metallic mineral products nec	0.315	*1.49*	1.154	*4.20*	-1.407	*6.93*	-0.062	*0.34*
Iron and steel	-0.330	*0.85*	2.761	*4.13*	-2.634	*2.39*	0.202	*0.21*
Basic non-ferrous metals	0.344	*2.28*	-0.161	*2.71*	-0.091	*0.78*	-0.092	*3.02*
Other metal products	0.562	*2.81*	0.470	*3.16*	-1.032	*3.29*	..	..
Machinery and equipment	0.942	*2.05*	0.495	*3.06*	-1.437	*2.61*	..	..
Public electricity generation	0.124	*0.36*	0.342	*0.55*	-0.062	*0.29*	-0.405	*0.73*
Private electricity generation	0.001	*0.07*	0.076	*1.60*	-0.059	*0.84*	-0.018	*0.75*
Gas production and distribution	0.023	*2.16*	1.776	*4.02*	-1.798	*4.00*	..	..
Water, sewerage and drainage	0.886	*6.19*	-0.044	*4.23*	-0.842	*6.12*	..	..
Construction	-0.001	*1.28*	0.001	*1.85*	0.000	*0.20*	..	..
Wholesale and retail trade	0.992	*3.85*	0.238	*2.01*	-1.230	*5.13*	..	..
Transport and storage	0.001	*2.23*	0.002	*14.55*	-0.004	*6.87*	0.001	*8.44*
Communication	0.309	*1.44*	-0.226	*1.79*	-0.083	*0.80*	..	..
Finance, insurance, property and business	..	..	..	..	..	..	..	..
Government administration and defence	-0.074	*0.26*	0.111	*0.35*	-0.081	*0.26*	0.044	*2.36*
Education, health and community services	-0.103	*0.45*	0.165	*0.91*	-0.052	*0.53*	-0.011	*0.35*
Accommodation, cultural and personal	1.256	*3.57*	-0.641	*2.65*	-0.558	*4.10*	-0.056	*3.35*

Note: 1. nec = not elsewhere classified. 2. Critical values: 10 per cent = 1.67, 5 per cent = 2.00, 1 per cent = 2.66.

Source: Author's estimations.

Appendix Table A6.4 **Price elasticities for coal demand, 1995**

Sub-sectors	ε_{41}		ε_{42}		ε_{43}		ε_{44}	
	Value	*t-score*	Value	*t-score*	Value	*t-score*	Value	*t-score*
Agriculture, forestry and fishing	..	..	..	..	..	..	..	..
Mining	0.034	*0.40*	0.289	*1.86*	-0.299	*1.89*	-0.024	*0.31*
Meat and meat products	-0.634	*4.05*	1.126	*6.52*	0.016	*0.11*	-0.508	*3.32*
Dairy products	0.083	*1.96*	0.091	*1.32*	-0.146	*1.94*	-0.028	*0.82*
Fruit and vegetable processing	0.099	*0.56*	0.380	*2.03*	0.123	*1.35*	-0.601	*4.54*
Oil and fat products	-1.623	*5.73*	1.612	*4.95*	0.546	*2.88*	-0.535	*3.59*
Flour mill and cereal food products	-0.060	*0.21*	0.947	*4.07*	0.331	*2.50*	-1.217	*4.72*
Bakery products	..	..	..	..	..	..	..	..
Other food products	-0.018	*0.34*	0.078	*2.71*	0.075	*1.46*	-0.134	*1.57*
Beverages and malt	1.007	*1.01*	-0.534	*0.90*	1.099	*3.18*	-1.572	*2.68*
Tobacco products	-9.879	*2.67*	-7.409	*3.38*	-2.667	*2.09*	19.955	*9.24*
Textile, clothing, footwear and leather	-0.385	*0.49*	2.272	*4.59*	-0.496	*2.59*	-1.391	*2.78*
Wood, paper products + Printing, publishing and recorded media	-0.050	*0.23*	0.674	*3.78*	-0.268	*4.80*	-0.356	*2.60*
Petroleum refining	..	..	..	..	..	..	..	..
Petroleum and coal products nec	..	..	..	..	..	..	..	..
Basic chemical products	-0.027	*0.43*	1.432	*8.30*	-1.314	*9.55*	-0.091	*1.04*
Other chemical products + rubber & plastic products	3.532	*3.51*	0.221	*0.34*	-0.547	*2.15*	-3.206	*3.75*
Glass and glass products	..	..	..	..	..	..	..	..
Ceramic products	-0.910	*2.13*	1.000	*2.12*	0.065	*0.22*	-0.155	*0.78*
Cement, lime, plaster and concrete products	0.152	*0.66*	-0.370	2.59	0.371	3.28	-0.153	*1.25*
Non-metallic mineral products nec	0.224	*0.31*	-0.091	*0.15*	-0.108	*0.34*	-0.025	*0.17*
Iron and steel	-0.006	*0.60*	0.014	*0.60*	0.004	*0.21*	-0.013	*0.36*
Basic non-ferrous metals	1.180	*2.37*	-0.552	*1.54*	-0.312	*3.02*	-0.316	*1.86*
Other metal products	..	..	..	..	..	..	..	..
Machinery and equipment	..	..	..	..	..	..	..	..
Public electricity generation	0.048	*1.20*	0.108	*1.65*	-0.021	*0.73*	-0.136	*1.84*
Private electricity generation	-0.266	*3.52*	1.083	*5.30*	-0.131	*0.75*	-0.686	*3.58*
Gas production and distribution	..	..	..	..	..	..	..	..
Water, sewerage and drainage	..	..	..	..	..	..	..	..
Construction	..	..	..	..	..	..	..	..
Wholesale and retail trade	..	..	..	..	..	..	..	..
Transport and storage	-1.689	*3.96*	0.818	*1.39*	1.661	*8.44*	-0.790	*2.35*
Communication	..	..	..	..	..	..	..	..
Finance, insurance, property and business	..	..	..	..	..	..	..	..
Government administration and defence	0.284	*0.35*	-0.520	*0.83*	1.237	*2.36*	-1.000	*1.38*
Education, health and community services	0.263	*0.52*	-0.166	*0.73*	-0.064	*0.35*	-0.033	*0.31*
Accommodation, cultural and personal	2.785	*5.92*	-2.127	*6.32*	-0.577	*3.35*	-0.081	*1.01*

Note: 1. nec = not elsewhere classified. 2. Critical values: 10 per cent = 1.67, 5 per cent = 2.00, 1 per cent = 2.66.

Source: Author's estimations.

7

Energy substitution possibilities: an application of a dynamic factor demands model

Synopsis

Using a dynamic model of factor demands and invoking homothetic separability, the demand for aggregate factor inputs and energy components is modelled separately for the Australian economy with a view to analysing the energy substitution possibilities. The aggregate choice model, summarised by a quadratic cost function, is specified in terms of energy, materials, labour and quasi-fixed capital. The fuel choice model, represented by a homothetic translog cost function, includes electricity, gas, oil and coal. To this end, the economy is divided into seven sectors: agriculture; mining; manufacturing; electricity, gas and water; construction; transport; and services; and the resulting demand systems are estimated using national-level annual data spanning the period from 1974 to 1998. Local curvature conditions are imposed on the underlying aggregate and fuel cost functions. The aggregate system is also treated for serially correlated errors but the fuel choice system is not, despite symptoms of serial correlation because of implausible elasticities resulting from the dual treatment.

The demand for aggregate energy input is found to be not very price sensitive. Energy and labour are mostly substitutes whereas energy and capital are long-run complements in all seven sectors, indicating that a carbon tax may slow down economic growth by retarding investment. Gas demand is relatively more (own) price sensitive compared to that of the other fuels. Also, significant substitution possibilities from coal and oil to gas are found, especially in manufacturing and power industries, which, together, consume more than 60 per cent of gross energy demand. Such substitution possibilities are favourable to reduced environmental impacts from energy use.

7.1 Introduction

The previous chapter estimated the inter-fuel substitution structure of the Australian economy by dividing it into 37 industries and categorising total energy use by industry into electricity, gas, oil and coal. Total energy demand by industry was taken as an exogenous variable because at the level of detail sought in the analysis, data on other factor aggregates – capital, labour, and non-energy materials – and output could not be obtained. However, in order to study the price responsiveness of energy in aggregate and the opportunities of substituting aggregate energy with other factors of production – capital, labour and materials – it is crucial to endogenise total energy demand along with that of the other inputs. This issue is tackled in this chapter by compromising at the level of industrial detail. A tradeoff is the likelihood of aggregation error.

In order to analyse the impact of significant energy price movements it is, however, crucial to consider a dynamic model of factor demands (Nadiri and Rosen 1969:458; Denny *et al.* 1981:231; Pindyck and Rotemberg, 1983:1066). Several dynamic models of factor demands have been used to analyse energy demand. Nadiri and Rosen (1969, 1973), for example, suggested a generalised version of the single-equation partial adjustment mechanism, involving systems of interrelated disequilibrium equations. This kind of generalised adjustment scheme permits disequilibrium in one factor market to influence the demand for the other factors, allowing for short-run overshooting possibilities.

Anderson and Blundell (1982, 1983, 1984) parameterised a static demand system as a vector error correction model (VECM) to introduce dynamics in the context of both input and commodity demand systems. The VECM nests within it Nadiri and Rosen's (1969) partial adjustment model and the static model with autoregressive errors.[1] However, in this model the parameters associated with the lagged variables are not identified, although the steady state parameters are identified. Recently, Allen and Urga (1999) derived a cost function capable of generating Anderson and Blundell type dynamic demand systems. In so doing, they also solved the parametric identification problem faced by Anderson and Blundell.

Constructed on the notion of the restricted cost or profit function introduced by Samuelson (1953) and developed later by Lau (1976) and McFadden (1978), Brown and Christensen (1981) formulated a restricted translog variable cost function for US agriculture. They derived both short and long-run elasticities by using Samuelson's (1953) famous tangency condition between short-run average cost curves and the corresponding long-run average cost curve.

A problem common to the above-mentioned and to other dynamic model specifications based on static optimisation is that they are unable to describe the time path to the long-run equilibrium, although most give a complete characterisation of short and long-run elasticities.

Berndt *et al.* (1980), on the other hand, developed a dynamic factor demands model that is explicitly based on dynamic economic optimisation principles and characterises completely short and long-run demand, as well as the path to a steady state equilibrium. Capital stock, a quasi-fixed factor input in this model, is subject to increasing marginal adjustment costs, that are assumed to result from internal disruptions within the firm.[2] Relying on Treadway's (1974) work in the partial adjustment/flexible accelerator literature, they employ an explicit solution for the optimal investment problem. This, in turn, requires them to represent the underlying production structure by a restricted variable quadratic cost function, in addition to assuming that producers have static expectations regarding factor and output prices.[3]

Pindyck and Rotemberg (1983) also proposed a dynamic system of factor demands that employs rational expectations regarding the evolution of output and input prices and is also explicitly based on dynamic optimisation principles in the presence of quadratic adjustment costs for the quasi-fixed factors, capital and labour. Their estimated model provides a complete description of short and long-run elasticities. They were, however, unable to calculate optimal factor demand trajectories due to the complexity of the underlying control problem which led them to perform simulations in a deterministic context to compute factor input responses to changes in factor prices.

This study employs the dynamic specification suggested by Berndt *et al.* (1980), as it completely summarises the time path to the steady state equilibrium. Two features of this approach are particularly attractive, given the crucial role of energy demand elasticities and the speed of adjustment of capital stock in response to various shocks in greenhouse gas mitigation cost studies. Firstly, the estimation of sectoral energy demand functions and of their components' demand, and hence inter-fuel substitution elasticities, recognises the dependence of energy demand not only on other variable factor inputs in the disequilibrium process but also on the quantities of quasi-fixed capital input. And, the fact that it is done in a dynamic optimisation context implies that the estimates of the short and long-run energy elasticities correspond to the Marshallian concept of the short and long-run elasticities. Secondly, the speed of adjustment of the capital stock to its long-run level after, for example, an energy price shock is endogenous and optimal at each point in time due, again, to the application of dynamic economic optimisation.

The rest of the chapter is organised as follows. Section 7.2 briefly discusses the dynamic factor demands model and derives the estimating equations of the aggregate choice and the fuel choice models. The data sources and methodologies used to construct the data set are explained in Section 7.3. The estimation results, including factor demand elasticities, are reported and discussed in the next section. The study is summarised in Section 7.5.

7.2 Model

7.2.1 Aggregate choice model

Following Berndt *et al.* (1981), the production structure of a firm is represented by an implicit production function of the following form:

$$F(E, M, L, K, \dot{K}, Q, t) = 0 \tag{7-1}$$

where Q is the level of output representing cost minimizing combinations of energy (E), material inputs including intermediate inputs except energy and raw materials (M), labour (L), quasi-fixed capital stock (K), net investment ($\dot{K}$) and technical change (t). If, in any particular period, accumulation or decumulation of capital takes place ($\dot{K} \neq 0$), output in that period falls, as resources are devoted to implementing the change in capital stock rather than producing output. This internal cost of forgone output caused by a change in capital stock is represented by the term $\partial Q / \partial \dot{K} < 0$. The level of investment thus affects the current level of output; the higher is the level of investment, the greater is the level of output forgone.[4]

Assuming that firms minimise the present value of the future stream of costs, the objective functional of a firm can be written as:

$$\Gamma(0) = \int_0^\infty e^{-rt} (P_E E + P_M M + WL \ + P_{IG} I_G) \ \ dt \tag{7-2}$$

where

P_E	=	Energy price index;
W	=	Hourly wage rate index
P_{IG}	=	Investment price index;
E	=	Real energy cost in millions of 1998 dollars;
M	=	Real cost of non-energy materials in millions of 1998 dollars;
L	=	Real labour cost in millions of 1998 dollars;
I_G	=	Gross investment, that is, $I_G = I + \delta K$, where I is net investment, K is net capital stock (both in millions of 1998 dollars) and δ is the depreciation rate;
r	=	After-tax rate of return.

The problem of the firm is to minimise the present value of the future stream of costs, $\Gamma(0)$, subject to the production function constraint (7-1). It is assumed in this minimisation problem that the level of output and technology are known and constant over time. Minimisation is accomplished by choosing the time paths of control variables, E, M, L and $\dot{K}$, and the state variable, K, such that minimisation of $\Gamma(0)$ is ensured given initial levels of labour, energy, materials and capital stock. In order to proceed further, the factor requirement function of labour is obtained by solving the implicit production function (7-1) for labour:

$$L = f(E, M, K, \dot{K}, Q, t) \tag{7-3}$$

Substituting (7-3) into (7-2), the optimisation problem is written as:

$$\Gamma(0) = \int_0^\infty e^{-rt} \left[P_E E + P_M M + Wf(E, M, K, \dot{K}, Q, t) + P_{IG} I_G \right] \, dt \tag{7-4}$$

The necessary conditions with respect to the variable factor inputs are:

$$\partial\Gamma(0) / \partial E = Wf_E + P_E = 0 \tag{7-5}$$

$$\partial\Gamma(0) / \partial M = Wf_L + P_M = 0 \tag{7-6}$$

The two first order conditions, (7-5) and (7-6), after a slight rearrangement, take the form:

$$f_E = -P_E / W = -p_e \tag{7-5a}$$

$$f_M = -P_M / W = -p_m \tag{7-6a}$$

The partial derivatives of the labour requirement function with respect to energy and material inputs are negative, as an increase in the availability of the latter factors reduces the number of labour hours needed to produce a given level of output. Given strict quasi-convexity of the production function, (7-5a) and (7-6a) are solved to obtain the short-run factor demand functions for energy and materials:

$$\overline{E} = \overline{E}(p_e, p_m, K, \dot{K}, Q, t) \tag{7-7}$$

$$\overline{M} = \overline{M}(p_e, p_m, K, \dot{K}, Q, t) \tag{7-8}$$

Using (7-7) and (7-8), gives the following cost function:

$$G = L + p_e \overline{E}(.) + p_m \overline{M}(.) = G(p_e, p_m, K, \dot{K}, Q, t) \tag{7-9}$$

The above cost function, G, is a restricted cost function, normalised by the wage rate. It is restricted because it is conditional on the level of output, capital stock and the rate of change of capital stock, that is, net investment. The corresponding expression for the minimum variable cost function can be obtained by multiplying the normalised cost function by the wage rate. Substituting the cost function in (7-9) into (7-2) gives:

$$\Gamma(0) = \int_0^\infty We^{-rt}\left[G(p_e, p_m, K, \dot{K}, Q, t) + p_i I_G\right] dt \tag{7-10}$$

where p_i is the normalised acquisition price of the quasi-fixed factor, capital stock. Substituting for $I_G = \dot{K} + \delta K$, the objective functional in (7-10) becomes:

$$\overline{\Gamma}(0) = \int_0^\infty e^{-rt}\left[G(p_e, p_m, K, \dot{K}, Q, t) + p_i \delta K\right] dt + \int_0^\infty e^{-rt} p_i \dot{K} dt \tag{7-11}$$

where $\overline{\Gamma}(0) = \Gamma(0)/W$. Integrating by parts, the last expression in (7-11) yields:

$$\int_0^\infty e^{-rt} p_i \dot{K} dt = \int_0^\infty e^{-rt} r p_i K dt + p_{i0} K_0 \tag{7-12}$$

Combining (7-11) and (7-12) yields:

$$\overline{\overline{\Gamma}}(0) = \int_0^\infty e^{-rt}\left[G(p_e, p_m, K, \dot{K}, Q, t) + uK\right] \tag{7-13}$$

where $\overline{\overline{\Gamma}}(0) = \overline{\Gamma}(0) - p_{i0} K_0$ and $u = p_i(r + \delta)$ is the normalised user cost of capital. The problem of minimising $\overline{\overline{\Gamma}}(0)$ with respect to the state variable, capital stock, and the control variable, net investment, is a standard one in optimal control theory. A current-valued Hamiltonion is set up:

$$H(K, \dot{K}, \lambda, t) = e^{-rt}\left[G(p_e, p_m, K, \dot{K}, Q, t) + uK\right] + \lambda \dot{K} \tag{7-14}$$

Given that H is convex in K due to the fact that G is convex in K, the necessary and sufficient conditions for a minimum are:

$$\partial H / \partial \dot{K} = 0 = e^{-rt} G_{\dot{K}} + \lambda \tag{7-15}$$

$$\partial H / \partial K = -\dot{\lambda} = e^{-rt} G_K + u e^{-rt} \tag{7-16}$$

where G_K and $G_{\dot{K}}$ are the partial derivatives of the normalised restricted cost function (NRCF) with respect to capital stock and net investment, respectively. In order to eliminate the co-state variable, λ, from (7-15) and (7-16), (7-15) is differentiated with respect to time to get:

$$-\dot{\lambda} = e^{-rt}\left[G_{K\dot{K}} \dot{K} + G_{\dot{K}\dot{K}} \ddot{K}\right] - r e^{-rt} G_{\dot{K}} \tag{7-17}$$

Equating (7-16) and (7-17) yields:

$$G_K + r G_{\dot{K}} + u = G_{K\dot{K}} \dot{K} + G_{\dot{K}\dot{K}} \ddot{K} \tag{7-18}$$

A steady state solution simplifies (7-18) to:

$$-G_{K^*} = u + r G_{\dot{K}^*} \tag{7-19}$$

where * in the two derivative expressions, G_{K^*} and $G_{\dot{K}^*}$, indicates that these are evaluated at the steady state point. The above simplification reflects the fact that, at a steady state, net investment, $\dot{K}$, and the rate of change of net investment, $\ddot{K}$, will be zero. The left hand side of (7-19) represents the marginal benefit to the firm of changing capital stock. The right hand side of the steady state solution, in contrast, is the marginal cost of a change in capital that consists of the user cost of capital plus the amortized marginal adjustment cost.

Treadway (1974) has shown that $\dot{K}$ can be generated from (7-19) as an approximate solution to the following differential equation:

$$\dot{K} = m^*(K^* - K) \tag{7-20}$$

where K^* is the steady state capital stock and m^* is the adjustment cost coefficient evaluated at the steady state point. Assuming that the cost function was globally quadratic, m^* is determined from a solution to the following quadratic form:

$$G^*_{\dot{K}\dot{K}} m^{*2} + rG^*_{K\dot{K}} m^* - (G^*_{KK} + rG^*_{K\dot{K}}) = 0 \tag{7-21}$$

The expression for the adjustment parameter, m^*, is obtained by solving the quadratic form (7-21) for the positive unit root as:

$$m^* = -1/2\left\{ r - \left[r^2 + \frac{4(G^*_{KK} + rG^*_{K\dot{K}})}{G_{\dot{K}\dot{K}}} \right]^{1/2} \right\} \tag{7-22}$$

In this expression the term $G^*_{K\dot{K}}$ is zero, owing to the assumption of stationarity. The adjustment parameter, which gives the proportion of the gap between actual and desired capital stock that is closed in each period, is a declining function of the after-tax rate of return, r.

In order to use this model empirically, the NRCF is chosen to be approximated by a quadratic specification, primarily for two reasons. Firstly, the elements of the Hessian matrix of second order partial derivatives are constants. This facilitates the linking of short and long-run elasticities. Secondly, in the case of a quadratic specification the underlying differential equation is linear, implying that the optimal path for the quasi-fixed factor, capital stock, is locally as well as globally valid. For the econometric investigation, it is further assumed that continuous changes in capital stock, $\dot{K}$, are represented by discrete changes, $\Delta K = K_t - K_{t-1}$, and that output in the current period, t, is a function of the capital stock in place at the beginning of the period, K_{t-1}. Following Watkins and Berndt (1992), the NRCF is chosen to be of the form:

$$
\begin{aligned}
G_t &= L + p_e E + p_m M = \\
&Q\left[\alpha_0 + \alpha_{0t} t + \alpha_E E + \alpha_M M + \alpha_{Mt} p_m t + \varepsilon_{Et} p_e t + 1/2(\alpha_{EE} p_e^2 + \alpha_{MM} p_m^2) + \alpha_{EM} p_e p_m\right] + \\
&1/2\alpha_{KK} K_{-1}^2 / Q + \alpha_K K_{-1} + \alpha_{Kt} K_{-1} t + \alpha_{EK} p_E K_{-1} + \alpha_{MK} p_M K_{-1} + \alpha_{\dot{K}t} \Delta K + \alpha_{\dot{K}} \Delta K + \\
&+ \alpha_{E\dot{K}} p_E \Delta K + \alpha_{M\dot{K}} p_M \Delta K + \alpha_{K\dot{K}} K_{-1} \Delta K / Q + 1/2\alpha_{\dot{K}\dot{K}} \Delta K^2 / Q
\end{aligned}
\tag{7-23}
$$

The adjustment (internal) cost function associated with capital stock can be obtained by combining all terms in (7-23) involving ΔK. The adjustment cost function, therefore, takes the form:

$$
\begin{aligned}
C(\Delta K) = {} & \alpha_{\dot{K}} \Delta K + \alpha_{\dot{K}t} \Delta K t + \alpha_{E\dot{K}} p_E \Delta K + \alpha_{M\dot{K}} p_M \Delta K + \\
& \alpha_{K\dot{K}} K_{-1} \Delta K / Q + 1/2\alpha_{\dot{K}\dot{K}} \Delta K^2 / Q
\end{aligned}
\tag{7-24}
$$

At a steady state equilibrium, when net capital accumulation is zero, that is, $\Delta K = 0$, total adjustment costs are zero, $C(\Delta K=0) = 0$.[5] Also, at the steady state equilibrium, the marginal adjustment cost must be zero. This imposes restrictions on the parameters of the adjustment cost function and thus on the NRCF. To see this, the expression for the marginal adjustment cost function is given:

$$
C'(\Delta K)_{\Delta K=0} = \alpha_{\dot{K}} + \alpha_{\dot{K}t} t + \alpha_{E\dot{K}} p_E + \alpha_{M\dot{K}} p_M + \alpha_{K\dot{K}} K^* / Q \tag{7-25}
$$

Clearly, for the marginal adjustment cost function to be zero in a steady state, the following restrictions must hold:

$$
\alpha_{\dot{K}} = \alpha_{\dot{K}t} = \alpha_{E\dot{K}} = \alpha_{M\dot{K}} = \alpha_{K\dot{K}} = 0 \tag{7-26}
$$

An application of Shephard's lemma to the cost function, G, in (7-23) gives the short-run demand functions for E and M:

$$
E / Q = \alpha_E + \alpha_{Et} t + \alpha_{EE} p_e + \alpha_{EM} p_m + \alpha_{EK} K_{-1} / Q \tag{7-27}
$$

$$
M / Q = \alpha_M + \alpha_{Mt} t + \alpha_{EM} p_e + \alpha_{MM} p_m + \alpha_{MK} K_{-1} / Q \tag{7-28}
$$

The short-run demand for labour is derived using the residual relationship:

$$
\begin{aligned}
L / Q = {} & G / Q - p_e E / Q - p_m M / Q = \\
& \alpha_0 + \alpha_{0t} t - 1/2(\alpha_{EE} p_e^2 + 2\alpha_{EM} p_e p_m + \alpha_{MM} p_m^2) + \\
& \alpha_K K_{-1} / Q + \alpha_{Kt} K_{-1} t / Q + 1/2\alpha_{KK} K_{-1}^2 / Q^2 + 1/2\alpha_{\dot{K}\dot{K}} \Delta K^2 / Q^2
\end{aligned}
\tag{7-29}
$$

In order to arrive at an expression for the steady state capital stock, the quadratic cost function specification in (7-24) is differentiated with respect to K. After imposing restrictions of a steady state equilibrium, the following expression for the derivative is obtained:

$$
G_{K^*} = \alpha_K + \alpha_{Kt} t + \alpha_{EK} p_e + \alpha_{MK} p_m + \alpha_{KK} K^* / Q \tag{7-30}
$$

Combining (7-30) with (7-19), after some manipulation, gives:

$$
K^* = -(\alpha_K + \alpha_{Kt} t + \alpha_{EK} p_e + \alpha_{MK} p_m + u_k)(Q / \alpha_{KK}) \tag{7-31}
$$

The difference equation characterising capital stock is re-written as:

$$\Delta K = m^*(K^* - K) \tag{7-32}$$

where

$$m^* = -1/2\left\{r - \left[r^2 + \frac{4\alpha_{KK}}{\alpha_{\dot{K}\dot{K}}}\right]^{1/2}\right\} \tag{7-33}$$

which is obtained by substituting $G_{KK} = \alpha_{KK}/Q$, $G_{\dot{K}\dot{K}} = \alpha_{\dot{K}\dot{K}}/Q$, and $G_{K\dot{K}} = \alpha_{K\dot{K}}/Q$ = 0 into the general expression for the adjustment parameter, (7-22). As m^* measures the proportion of the gap between equilibrium and actual capital stock that is filled over a period of a year, it is required to be a positive fraction, $0 < m^* \leq 1$. It can be shown that a sufficient condition for this inequality to hold globally, given a non-negative *r*, is that $\alpha_{KK}/\alpha_{\dot{K}\dot{K}} < 1$. Also, for the own-price elasticity of capital to be negative it is required that $\alpha_{KK} > 0$. Both conditions are met simultaneously if the two parameters satisfy the following inequality restriction $\alpha_{\dot{K}\dot{K}} > \alpha_{KK} > 0$, which is imposed at the estimation stage. Combining (7-31), (7-32) and (7-33), after some re-arrangement, gives an equation for the net investment function:

$$\Delta K/Q = -1/2\left\{r - \left[r^2 + \frac{4\alpha_{KK}}{\alpha_{\dot{K}\dot{K}}}\right]^{1/2}\right\} \left[\frac{1}{\alpha_{KK}}(\alpha_K + \alpha_{Kt}t + \alpha_{EK}p_e + \alpha_{MK}p_m + u_k) + K_{-1}/Q\right] \tag{7-34}$$

The dynamic model derived above helps compute short and long-run elasticities, which describe the behaviour of factor demands over time. In the context of this four-input demand model, short-run elasticity expressions are derived under the assumption of fixed capital. The corresponding long-run elasticities assume that capital stock has adjusted to its steady state level, K^*, following a price shock. Short-run elasticities for the variable factors are calculated as:

$$\varepsilon^{SR}_{V_iP_j} = \frac{P_j}{V_i}\left(\left.\frac{\partial V_i}{\partial P_j}\right|_{K=\bar{K}}\right) \qquad i,j = E,M,L \tag{7-35}$$

The corresponding long-run elasticities are derived from:

$$\varepsilon^{LR}_{V_iP_j} = \frac{P_j}{V_i}\left(\left.\frac{\partial V_i}{\partial P_j}\right|_{K=\bar{K}} + \frac{\partial V_i}{\partial K^*}\frac{\partial K^*}{\partial P_j}\right) \qquad i = E,M,L;\, j = E,M,L,K \tag{7-36}$$

The long-run own and cross-price elasticities of capital are obtained from:

$$\varepsilon_{KP_j}^{LR} = \frac{P_j}{K^*}\frac{\partial K^*}{\partial P_j} \qquad j = E, M, L, K \tag{7-37}$$

The short-run own-price elasticities of energy and materials are globally negative if α_{EE} and α_{MM} are negative. It cannot be ensured that the labour demand elasticity is globally negative because of the complications caused by its role as a normalising variable. However, local negativity at a single point can easily be imposed by re-scaling prices such that all price variables assume a value of one at the concavity point. This local negativity requires the restriction $-\alpha_{EM} > (\alpha_{EE} + \alpha_{MM})/2$, which is imposed for 1998.[6]

This completes the derivation of the estimating equations and elasticity expressions for the dynamic model. In the empirical part of this chapter the short-run demand equations for *E*, *M*, *L,* along with the net investment equation (7-34), are estimated in SHAZAM, Version 8, using the non-linear iterative regression procedure. The estimated model in Section 7.4 incorporates a simple autocorrelation treatment, a diagonal autocovariance matrix, for each industry except agriculture, as in the baseline results the DW for the non-agriculture industries were typically low.[7]

7.2.2 Fuel choice model

Implicit in this analysis is the assumption that the underlying production structure of a firm is weakly separable in variable factor aggregates. In the context of the aggregate energy input (*E*), for instance, the assumption implies that the marginal rates of substitution between any two energy sources are independent of the quantities of the other variable factor inputs. This restriction on the production structure of the firm translates into the following form of the production function:

$$F(E(E_1, E_2, ..., E_n), M, L, K, \Delta K, Q, t) = 0 \tag{7-38}$$

The corresponding normalised cost function takes the form:

$$G = G(\frac{P_E(P_{E1}, P_{E2}, ..., P_{En}, K_{-1}, Q, t)}{P_L}, \frac{P_M}{P_L}, \frac{K_{-1}}{Q}, \frac{\Delta K}{Q}, Q, t) \tag{7-39}$$

The un-normalised unit energy cost function, P_E, is proposed, following Denny *et al.* (1981), to be approximated by a translog specification:

$$\begin{aligned} \log P_E = \log\gamma_0 + \sum_{i=1}^{n}\gamma_i \log P_{Ei} + 1/2\sum_{i=1}^{n}\sum_{j=1}^{n}\gamma_{ij}\log P_{Ei}\log P_{Ej} + \\ \sum_{i=1}^{n}\gamma_{iK}\log P_{Ei}\log(\frac{K_{-1}}{Q}) + \sum_{i=1}^{n}\gamma_{it}\log P_{Ei}t \end{aligned} \tag{7-40}$$

Application of Shephard's lemma to the above unit energy cost function gives the fuel share system:

$$\frac{\partial \log P_E}{\partial \log P_{Ei}} = w_{Ei} = \gamma_i + \sum_{j=1}^{n} \gamma_{ij} \log P_{Ej} + \gamma_{iK} \log(\frac{K_{-1}}{Q}) + \gamma_{it} t \tag{7-41}$$

where w_{Ei} is the fuel cost share of the ith fuel in total energy costs. The fuel cost share system (7-41) is estimated first which gives an estimate of $\log P_E$ which is used as an instrumental variable in the aggregate model, as energy price is an endogenous variable owing to the assumption of weak separability.

As in the previous chapter, the fuel choice analysis in this study faced two statistical problems: concavity violations and serial correlation. Curvature violations were quite frequent while the serial correlation problem was relatively mild, probably due to a comparatively rich formulation of the unit energy cost function. Local curvature conditions were imposed at the last sampled year, 1998, while the autocorrelation problem was not addressed, as it implies only a relatively large scatter around (still) unbiased population parameters.[8]

Total energy use by each sector is divided into electricity, gas, oil and coal. The following four-equation system, therefore, is estimated as an energy submodel:

$$\begin{aligned}
w_{E1} &= \gamma_1 + \gamma_{11} \log P_{E1} + \gamma_{12} \log P_{E2} + \gamma_{13} \log P_{E3} + \gamma_{14} \log P_{E4} + \gamma_{1t} t + \gamma_{1K} \log\left(\frac{K_{-1}}{Q}\right) + U_1 \\
w_{E2} &= \gamma_2 + \gamma_{12} \log P_{E1} + \gamma_{22} \log P_{E2} + \gamma_{23} \log P_{E3} + \gamma_{24} \log P_{E4} + \gamma_{2t} t + \gamma_{2K} \log\left(\frac{K_{-1}}{Q}\right) + U_2 \\
w_{E3} &= \gamma_3 + \gamma_{13} \log P_{E1} + \gamma_{23} \log P_{E2} + \gamma_{33} \log P_{E3} + \gamma_{34} \log P_{E4} + \gamma_{3t} t + \gamma_{3K} \log\left(\frac{K_{-1}}{Q}\right) + U_3 \\
w_{E4} &= \gamma_4 + \gamma_{14} \log P_{E1} + \gamma_{24} \log P_{E2} + \gamma_{34} \log P_{E3} + \gamma_{44} \log P_{E4} + \gamma_{3t} t + \gamma_{4K} \log\left(\frac{K_{-1}}{Q}\right) + U_4
\end{aligned} \tag{7-42}$$

where 1 = electricity; 2 = gas; 3 = oil; 4 = coal; γ_{iK} is the coefficient of capital stock; γ_{it} is the coefficient of the trend variable in the ith share equation; and t is the trend variable. Technical change is ith fuel using (saving) if γ_{it} is positive (negative). It is said to be neutral if γ_{it} is zero. For the purposes of estimating the share system, the coal share equation was arbitrarily dropped and the remaining three equations were estimated simultaneously in SHAZAM using the non-linear seemingly unrelated regression procedure. All parameters of the deleted equation were recovered with the help of the demand system restrictions.

For the translog model the inter-fuel price elasticities with E constant are computed from:

$$\varepsilon_{ii}^{E=\bar{E}} = \frac{\gamma_{ii} + w_{Ei}^2 - w_{Ei}}{w_{Ei}} \qquad i = 1,2,3,4 \tag{7-43}$$

$$\varepsilon_{ij}^{E=\bar{E}} = \frac{\gamma_{ij} + w_{Ei} w_{Ej}}{w_{Ei}} \qquad i, j = 1,2,3,4; i \neq j \tag{7-44}$$

The corresponding short-run elasticities with Q constant can be derived as:

$$\varepsilon_{ij}^{SR} = \varepsilon_{ij}^{E=\bar{E}} + \varepsilon_{EE}^{SR} w_{Ej} \qquad i, j = 1,2,3,4 \tag{7-45}$$

Finally, the long-run inter-fuel price elasticities with Q constant are obtained from:

$$\varepsilon_{ij}^{LR} = \varepsilon_{ij}^{SR} + \varepsilon_{KE}^{LR} (\gamma_{iK} + \frac{\partial E}{\partial K^*} \cdot \frac{K^*}{E} \cdot w_{Ej}) \qquad i, j = 1,2,3,4 \tag{7-46}$$

or

$$\varepsilon_{ij}^{LR} = \varepsilon_{ij}^{SR} + \varepsilon_{KE}^{LR} (\gamma_{iK} + \varepsilon_{EK^*}^{K^*} \cdot w_{Ej}) \qquad i, j = 1,2,3,4 \tag{7-47}$$

where $\varepsilon_{EK^*}^{K^*}$ is the elasticity of aggregate energy demand with respect to the amount of the steady state capital stock employed.

7.3 Data

The study uses national-level annual data spanning the period from 1974 to 1998, that is, 25 years. 1974 is the earliest year for which detailed energy use data are available. As mentioned previously, for the purposes of this study the non-residential economy is divided into seven industries (see Table 7.1 for sector definitions). The quantity data on various fuels were drawn from 'Australian Energy: Market Developments and Projections to 2014-15' published by the Australian Bureau of Agricultural and Resource Economics (ABARE) (Bush *et al.* 1999). The corresponding fuel price data were taken primarily from the Australian Gas Association (AGA 1994,1998) and O'Dwyer and Hu (1998). A discussion on fuel quantities is given in Chapter 2, and a brief analysis of prices is presented in the previous chapter (Section 6.3).

Analysis in this chapter, however, departs from that in the previous chapter by including data for the period from 1996 to 1998. Indeed, this chapter, as distinct from the previous one, uses relatively aggregate data which are available for the above-mentioned years but not at the level of detail sought in the previous chapter. The following paragraphs describe the various data sources and methodologies employed to construct the data set used to estimate the aggregate choice model.

Total number of hours worked and hourly wage rates by sector were constructed using time series data on the number of people employed by sector, average weekly hours worked by sector and compensation of employees by sector. Information on the number of people employed and weekly hours worked were taken from 'Labour Force, Australia' (ABS Catalogue No. 6203). The compensation of employees data including wages, salaries and supplements were drawn from 'Australian System of National Accounts' (NA) (ABS Catalogue No. 5204). Total number of hours worked were obtained by multiplying the number of people employed by average weekly hours worked. The corresponding wage rate for each sector was obtained by dividing the compensation of employees by total number of hours worked.

Table 7.1 **Industrial classification**

Division	Title	Short name(s) used
A	Agriculture, forestry and fishing	Agriculture
B	Mining	Mining
C	Manufacturing	Manufacturing
D	Electricity, gas and water	E-G-W / Power
E	Construction	Construction
I+J	Transport and storage + Communications	Transport
F+G+H+K+L+ M+N+O+P+Q	Wholesale trade + Retail trade + Accommodation, cafes and restaurants + Finance and insurance + Property and business services + Government administration and defence + Education + Health and community services + Cultural and recreational services + Personal and other services	Services / Commercial

Source: Bush *et al.* 1999. *Australian Energy: market developments and projections to 2014-15*, Australian Bureau of Agricultural and Resource Economics, Canberra.

Estimates of capital stock, consumption of fixed capital and gross fixed capital formation, at both current and average 1998 dollars, were taken from 'Australian National Accounts: Capital Stock' (ABS Catalogue No. 5221). The corresponding data on the after-tax rate of return by industry/sector were also drawn from the same publication, that is, ABS Catalogue No. 5221. The acquisition price of capital was obtained by dividing the nominal capital stock by the corresponding real capital stock.

Current dollar estimates of material inputs, including energy, and gross value of output for the period under consideration, 1974 to 1998, were constructed by combining two information sources, NA and 'Australian National Accounts: Input-Output Tables' (I-O) (ABS Catalogue No. 5209). The main source in this respect has been the I-O tables which provide highly disaggregated information on a whole range of variables including gross value of output, materials used, employment, and value-added, etc. by industry.

From the study's viewpoint, however, this data set has a number of limitations. Firstly, the I-O values differ generally from their NA counterparts, which is the most authentic source of information on macro variables, including incomes and prices.

Secondly, the I-O tables are not comparable over time due to varying coverage and definitions. Thirdly, the I-O tables are not available for the entire period under consideration.[9]

The I-O based coefficients or ratios – the ratio of value-added to the gross value of output, for instance – are expected, however, to be comparable over time. A consistent time series on the current dollar output, for instance, is obtained by multiplying the output-value-added ratio and the industrial value-added from the NA. Similarly, the ratio of material inputs to output is multiplied with the above-mentioned output variable to obtain a consistent time series on materials. Data for the missing years were constructed by assuming that the value-added output ratio and materials-output ratio for the missing years between two points change at a constant proportionate rate.

Both materials and output price indices for agriculture, manufacturing and construction were drawn from various ABS publications.[10] The two price indices for agriculture were obtained by dividing the current dollar series by the corresponding constant dollar series supplied by the ABS from unpublished sources on request. The price indices for the remaining sectors – mining, E-G-W, transport and services – could not be obtained. As a consequence, it was assumed that material inputs are weakly separable from the variable inputs in these industries. The output variable for these sectors, therefore, is defined as the sum of GDP and energy expenditure. The variable cost for these sectors thus consists of labour and energy costs.

The fuel choice model for agriculture consists only of two fuels, electricity and oil, as gas and coal use by the sector is almost non-existent. Similarly, the energy submodel for the construction sector does not consider coal fuel due again to its negligible use. The remaining sectors, that is, mining, manufacturing, E-G-W, transport and services, comprise the four-equation fuel cost share system.

Most of the data on capital stock, labour and prices, including material and output prices, were downloaded from the AUSSTATS database. This service provides online information on more than 90 thousand time series, mainly from the ABS sources, both published and unpublished. The service also contains data from the Reserve Bank of Australia and OECD publications.

7.4 Results

7.4.1 Regression

Non-linear maximum likelihood estimates of the fuel choice model are presented in the Appendix Table 7.1. Values in parentheses reflect the probability at which the respective coefficient is statistically different from zero. Both individual and system R^2s are reported at the bottom of the table. Individual R^2 across equations are fairly large – higher than 0.7, implying that predicted fuel cost shares track closely the actual shares. The system R^2 ($\widetilde{R}^2$), in contrast, is close to unity in nearly all equations, reflecting that the null hypothesis of slope coefficients simultaneously being zero is rejected easily. The goodness of fit as shown by individual R^2s and $\widetilde{R}^2$ should, however, be taken with caution because the problem of serial correlation has not been taken care of.

Capital stock is missing from the agriculture and manufacturing sector models because the parameter estimates involved were simultaneously not significant. Most of the remaining parameters are estimated reasonably precisely. In the case of agriculture, for example, all parameters are significant at the 1 per cent level of significance. The service industry contains only one parameter that is not significant at the 1 per cent level of significance. This number increases to two for manufacturing and three for mining. The construction industry contains the highest number of insignificant coefficients, seven out of a total of 15, followed by the power sector with five insignificant parameters. All sectors combined, there are 21 coefficients that are not significant at the 95 per cent level of confidence (18 insignificant coefficients at the 90 per cent level).

Technical progress that took place during the past two and a half decades, as measured by a simple time trend, has been electricity and gas consuming with, however, two exceptions. In construction and mining the electricity bias is not obvious because the respective coefficients are not statistically significant. Technical change has been oil saving in all sectors except construction which depends almost totally on oil for its energy requirements. Significant savings in coal use on account of technical progress are estimated to have occurred in mining, manufacturing and services. Technical change has, however, been coal using in E-G-W, which relies very heavily on this fuel, especially for power generation in the public sector.

The discussion now moves on to the corresponding aggregate choice model results that are presented in Appendix Table A7.2.

Individual R^2 vary greatly across equations of a given sector. Generally, they are the lowest for investment and highest for energy, implying a poor fit of the investment demand function. Interestingly, Watkins and Berndt's (1992) estimates of the investment demand function for Canadian manufacturing and iron and steel were also relatively poor. The system R^2, as with the fuel choice model, is very high at close to unity, implying an excellent overall fit, despite weaknesses in some of the individual equations.[11] The estimates of autocorrelation coefficients across equations/industries are fairly high, nearly unity in many instances, indicating the presence of strong autocorrelation. In the agriculture sector, the null hypothesis of an autoregressive error model, with diagonal autocovariance matrix, was rejected.

As far as the significance of individual parameter estimates is concerned, the agriculture and service industries again outperform the other sectors with only one insignificant coefficient at the 5 per cent level of significance in each case, α_{EE}. The construction sector, in contrast, performs poorly with seven insignificant parameter estimates. Manufacturing with six insignificant coefficients and mining and E-G-W with five poorly estimated parameters follow it. As a whole, there are 26 insignificant parameters that are insignificantly estimated at the 5 per cent level. This is a fairly large number in relation to a total of 85 structural parameters across seven industries.

The parameter characterising capital stock adjustment across industries, m^*, is also reported in the lower part of the Appendix Table A7.2. A low value of m^* indicates that, in response to an exogenous shock, firms adjust capital stocks relatively slowly. A relatively high m^*, on the other hand, implies that a significant gap between desired and actual capital stock is filled in each year. On average, this parameter takes a value of around 0.2 across seven industries, indicating that approximately 20 per cent of the gap between desired capital stock and the actual capital stock held by a firm at the beginning of the period is filled within a year. This adjustment factor, however, varies greatly across industries. According to these findings, capital stock is estimated to adjust very slowly to the equilibrium level in manufacturing and construction. In the construction sector, for instance, less than 2 per cent of the discrepancy is removed over a period of one year. The corresponding figure for the manufacturing sector is 4 per cent. Interestingly, the capital stock is found to adjust rather quickly in E-G-W and mining. More than 40 per cent of the gap between actual and desired levels of capital is filled in one year in these two sectors.

7.4.2 Elasticities

The estimates of both aggregate and fuel choice model price elasticities for 1998 are presented in the Appendix Tables A7.3 to A7.9. The top panel in each table reports the aggregate choice model elasticities for each sector, whereas the fuel choice elasticities for the corresponding sector are given in the lower panel of the table. Note that energy and capital are long-run complements across all industries. An increase in energy prices, associated with environmental legislation for instance, can therefore be expected to result in an economywide slow down in investment and hence economic growth. While the international literature on the nature of the relationship between the two factors is large, there have been very few studies in the Australian context. Turnovsky *et al.* (1982) and Turnovsky and Donnelly (1984) found the two factor aggregates were substitutes in the iron and steel industry and aggregate manufacturing.[12] In contrast, Truong (1985) found E-K complementarity for New South Wales manufacturing.

The nature of the relationship between energy and labour is not so obvious, partly because of the difference in short and long-run responses. The two factors are short and long-run substitutes in the mining, E-G-W, transport, and commercial sectors. In agriculture and manufacturing, the results tend to favour a complementary relationship, whereas in construction E-L are leaning towards substitution. These results should, however, be taken cautiously as the substitute relationship, both short and long-run, is found in all those industries except construction in which the assumption of weak separability between energy and non-energy material inputs has been employed.

Following Berndt and Wood (1979) on this energy-labour relationship issue, the cross-price elasticities, which are estimated from a production function that is based on weak separability between KLE and M, can be interpreted as gross price elasticities rather than net price elasticities. This is because the former elasticities do not account for substitution between the KLE aggregate and M. Following this line of argument, the energy-labour substitute relationship found in the above KLE cases could very well be a complementary relationship between the two factors in the context of an aggregate production function. This can be seen more clearly from the following expression that relates the gross price elasticity of energy demand with respect to the price of labour (ε^{g}_{EL}) to the corresponding net price elasticity (ε^{n}_{EL}):

$$\varepsilon^{n}_{EL} = \varepsilon^{g}_{EL} + w^{g}_{L}\varepsilon_{VV} \tag{7-48}$$

where w^{g}_{L} is the labour cost share in the KLE aggregate and ε_{VV} is the own-price elasticity of the KLE aggregate in the weakly separable production function. As ε_{VV} is expected to be negative in a well-behaved production function, the E-L substitute relationship found above in the KLE cases is expected to become at least moderate if not turn into a complementary relationship.

In other results relating to the aggregate choice model elasticities, energy and material inputs are substitutes in agriculture, manufacturing and construction. Capital stock and materials are also characterised by the same relationship. Materials and labour are substitutes in the manufacturing and construction sectors, both in the short and long-run. In agriculture, in contrast, the factor aggregates are substitutes in the short-run but complements in the long-run. Capital and labour are long-run substitutes in the agriculture, mining, power, transport and commercial sectors. In manufacturing and construction, however, the relationship is slightly complicated as the elasticity of labour with respect to the user cost of capital is negative, although the elasticity of capital with respect to the wage rate is positive.

It is worth noting that long-run elasticities sometimes depart sharply from their short-term counterparts for the aggregate choice model. This is particularly true in the case of agriculture where long-run elasticities of labour, especially own-price elasticities and with respect to the material input price, are greatly different from their short-run counterparts. In order to understand the source of the problem the expression for long-run elasticity is re-written as:

$$\varepsilon_{V_iP_j}^{LR} = \frac{P_j}{V_i}\left(\left.\frac{\partial V_i}{\partial P_j}\right|_{K=\bar{K}} + \frac{\partial V_i}{\partial K^*}\frac{\partial K^*}{\partial P_j}\right) \qquad i = E, M, L; j = E, M, L, K \qquad (7\text{-}49)$$

The second expression in the above elasticity expression is multiplied and divided by K^* to obtain:

$$\varepsilon_{V_iP_j}^{LR} = \frac{P_j}{V_i}\left.\frac{\partial V_i}{\partial P_j}\right|_{K=\bar{K}} + \frac{\partial V_i}{\partial K^*}\frac{K^*}{V_i}\frac{\partial K^*}{\partial P_j}\frac{P_j}{K^*}, \qquad i = E, M, L; j = E, M, L, K \qquad (7\text{-}50)$$

or

$$\varepsilon_{V_iP_j}^{LR} = \varepsilon_{V_iP_j}^{SR} + \varepsilon_{V_iK^*}^{K^*} \times \varepsilon_{K^*P_j}^{LR}, \qquad i = E, M, L; j = E, M, L, K \qquad (7\text{-}51)$$

The long-run elasticity of the ith variable factor with respect to the price of the jth factor, therefore, equals the corresponding short-run elasticity plus the elasticity of V_i with respect to quantity K, times the elasticity of capital with respect to the price of the variable factor involved. Capital is generally not very sensitive to factor prices, as the elasticity involved is typically less than 0.5 (in absolute terms). A high value of the long-run elasticity, therefore, is mostly associated with the high sensitivity of the variable factor to the amount of capital employed. Indeed, in agriculture, the elasticity of labour with respect to quantity K is nearly -10, which results in very high long-run responses despite relatively insensitive capital demand.[13]

The demand for aggregate energy is not very (own) price responsive. In all but manufacturing and construction, the elasticity is less than 0.1 in absolute terms, even in the long-run, indicating the indispensable nature of the resource in most production processes. Conversely, energy demand in construction and manufacturing is relatively price sensitive. In response to a 1 percent rise in the energy price, aggregate energy demand is expected to shrink by nearly 0.7 per cent once capital stock has adjusted to its long-run level after the energy price shock. Despite very similar long-run energy elasticities in the two industries, the corresponding short-term responses are very different. In manufacturing the short-term elasticity is almost 50 per cent of the long-term one, whereas in the construction sector the difference between the two responses is negligible despite very similar adjustment parameters. Indeed, in the construction industry energy demand is relatively independent of capital stock, which in turn is not very responsive to energy price variations. An interaction between these two factors leads to a relatively small difference in the two responses.

In the agriculture sector not only is energy demand independent of own-price, but there is also no sign of fuel switching between electricity and oil (the two main fuels used by the sector), even in the long-run. Considerable fuel substitution (complementary) possibilities exist in other industries, especially in manufacturing and E-G-W. In the manufacturing sector, for instance, electricity is used as a substitute for oil and coal. Electricity and gas, and oil and coal, in contrast, are complementary fuels within the sector. Similarly, complementarity is found in the use of electricity and oil, and oil and coal in the power industry. The other fuel combinations, that is, electricity-coal, electricity-gas, gas-oil and gas-coal are substitutes.

Significant substitution possibilities from coal to gas exist in manufacturing and E-G-W, which together employ more than 60 per cent of gross national energy. Not only is the long-run own-price elasticity of gas in these two industries quite high, $\varepsilon_{22}^{LR} \cong -0.8$, but the cross-price elasticities between the fuels are also fairly large, especially that of gas with respect to the coal price. A 10 per cent sustained increase in coal price is expected to reduce coal use in manufacturing by 3.5 per cent and increase gas use by more than 2 per cent in the equilibrium state. The same price change is associated with a nearly 2 per cent reduction in coal use and more than 5 per cent increase in gas demand in the power sector. Given the sheer size of coal consumption by the power sector, this translates to a significant reduction in coal consumption and hence emissions, especially those of CO_2.

In the construction industry – a small energy-using sector that relies mostly on oil – electricity and oil are complements whereas electricity-gas and gas-oil are substitute relationships. The fuel price elasticities involving electricity and gas are relatively large, indicating that the demand for the two fuels in this sector is not only own-price responsive but is also greatly influenced by the prices of other fuels. The demand for oil, on the other hand, is virtually independent of the electricity and gas prices. The unusually large share of oil in total energy use – nearly 99 per cent – explains these results.

Unlike the construction sector, the transport sector fuel cross-price sensitivities are relatively small, despite sharing a very similar fuel structure with the construction industry – large oil users. Given the special fuel structure of the two sectors, the fuel elasticities, it should be noted, embody limited usefulness.

Gas-coal and oil-coal are complementary relationships in the service industry which relies on electricity and gas for most of its energy needs. The remaining cross-price elasticities are all positive, implying that these fuels are substitutes. In the commercial sector, like most other industries, electricity demand is least own-price sensitive. Coal demand in contrast is the most own-price sensitive, followed by gas and oil. Gas demand is almost as responsive to the electricity price as it is to the gas price, reflecting substitution potential from electricity to gas.

7.5 Summary

The demand for aggregate factor inputs and fuel sources by the Australian economy was modelled and estimated with a view to analysing the energy substitution possibilities. A dynamic model of factor demands that is based explicitly on dynamic economic optimisation principles was employed. Capital stock, a quasi-fixed factor, was assumed to be subject to quadratic adjustment costs, resulting from internal disruptions within the firm. To this end, the non-residential sector economy was divided into seven sectors: agriculture; mining; manufacturing; construction; electricity, gas and water; transport, storage and communications; and services.

The production structure of each industry, specified in terms of energy, non-energy materials, labour and capital, was approximated by a quadratic cost function. The corresponding fuel structure, specified in terms of electricity, gas, oil and coal, was represented by a homothetic translog cost function. The two models – the aggregate choice model and the fuel choice model – were estimated separately for each of the seven industries using national-level annual time series data for the period from 1974 to 1998. For mining, electricity, gas and water, transport and service industries, output and material price deflators were not available. As a result, the assumption of weak separability between non-energy materials and other factors was invoked for the four industries.

Local curvature conditions for 1998 were imposed on both cost functions due to frequent curvature violations. The resulting cost functions were generally well-behaved and not just at the concavity point. The aggregate choice model was also treated for serially correlated errors, using a diagonal autocovariance matrix. The fuel choice model was not corrected for the problem partly because of the complications caused by the curvature restrictions and partly because of the small number of observations. The main findings are summarised below.

- Energy and labour are substitutes both in the short and long-run in most industries, whereas energy and capital are long-run complements in all industries.
- Capital and labour are long-run substitutes in five industries. In manufacturing and construction industries, however, the elasticity of labour with respect to capital is negative, whereas the elasticity of capital with respect to labour is positive.
- The demand for aggregate energy input is not very (own) price sensitive, even in the long-run. Indeed, in five industries the energy own-price elasticity is less than 0.1 (in absolute terms). In the remaining two industries, manufacturing and construction, it is around -0.6.
- In agriculture the demand for energy is not only independent of own-price but also no substitution possibilities are found between electricity and oil, the two main fuels used by the sector.
- Generally, electricity demand is the most price inelastic, whereas the demand for gas is the most elastic of all fuels.
- Complementarity in fuel consumption is found in some industries, especially in the case of electricity-oil, oil-coal, and gas-coal pairs. The dominant feature characterising inter-fuel relationships, however, is substitutability.
- Significant substitution possibilities from oil and coal to gas exist in the manufacturing and electricity, gas and water industries, which together use more than 60 per cent of gross national energy.

Notes

[1] See Berndt and Savin (1975) for an application of this model.

[2] Extension to the case of more than one quasi-fixed factor is straightforward, see, for instance, Morrison and Berndt (1981) and Rezitis *et al.* (1998).

[3] The quadratic specification has certain advantages over most other specifications. First, the Hessian matrix of second-order partial derivatives is a matrix of constants, which greatly facilitates the linking of short and long-run responses. Second, the estimated (optimal) investment equation is globally and locally valid, as the underlying differential equation approximating investment is linear due to the quadratic cost function specification (Denny *et al.* 1981:236-7).

[4] The derivation of the aggregate choice model in this subsection and that of the fuel choice model in the next subsection draws heavily from Berndt *et al.* (1981), Denny *et al.* (1981) and Watkins and Berndt (1992).

[5] Implicit in this expression for the adjustment costs, which are a function of net investment, is the assumption that replacement investment is frictionless; that is, replacement investment does not generate internal costs of adjustment in terms of output forgone. An alternative to this is to formulate the adjustment costs as a function of gross investment. Watkins and Berndt (1992) modelled the Canadian manufacturing and iron and steel industries' factor demands under both net investment and gross investment formulations and found significant and systematic differences in results. Pindyck and Rotemberg (1983), on the other hand, did not find any significant difference between the two formulations for US manufacturing. This study chose to employ the net investment version, primarily because the number of parameters increases significantly under the gross investment formulation.

[6] Of course, there is no *a priori* reason to expect a cost function representing an industry, an aggregate of firms, to be concave in factor prices, as a well-behaved cost function is an implication of optimising behaviour on the part of a firm. It is, however, a common practice to impose curvature restrictions on flexible specification(s) representing an aggregate of firms.

[7] The null hypothesis of an autoregressive error model was rejected in the case of agriculture.

[8] As in the previous chapter, simple autocorrelation treatment – the same autocorrelation coefficient across all fuel share equations – was considered; however, the resulting elasticities from this dual treatment were implausible. As a consequence, the autocorrelation problem is not treated. For a detailed discussion on the twin problems of curvature violations and autocorrelation, see Section 6.2 of the previous chapter.

[9] The tables are available for the following years: 1995, 1994, 1993, 1990, 1987, 1984, 1983, 1982, 1981, 1980, 1979, 1978, 1975, 1969, and 1963.

[10] The following Australian Bureau of Statistics (ABS) publications on prices were relied upon to obtain the output and material price data on the three sectors: Price Indexes of Materials Used in Manufacturing Industries, Australia, ABS Catalogue No. 6411.0; Price Index of Articles Produced by Manufacturing Industry, Australia, ABS Catalogue No. 6412.0; Price Index of Materials Used in Building Other Than House Building, Six State Capital Cities, ABS Catalogue No. 6407.0; and Price Index Of Materials Used in House Building, Six State Capital Cities, ABS Catalogue No. 6408.0.

[11] In fact, the individual R^2 is not a very appropriate tool with which to gauge the goodness of fit of an estimator in the context of a system. This is so mainly because the maximum likelihood (ML) procedure minimises the determinant of the residual cross product matrix and not individual sum of squares. An individual R^2 could very well be negative, as the sum of residuals is not necessarily zero. On the other hand, the system R^2, as a goodness of fit measure, should be taken cautiously as typically it is very high.

[12] Denny *et al.* (1981) found energy and capital to be complementary factors for most US manufacturing sector industries. They also analysed the Canadian manufacturing sector by dividing it into 18 industries and found complementarity in only six cases. Pindyck and Rotemberg (1983) found energy and capital to be long-run complements for US manufacturing using the Berndt and Wood (1975) data set.

[13] Recently, Rezites *et al.* (1999), using a dynamic demand system based on a quadratic value function, have reported long-run elasticities for the US cigarette manufacturing industry that are quite large (in absolute terms), especially those relating to materials.

Appendix Table A7.1 **Non-linear maximum likelihood parameter estimates, fuel choice model**

Parameters	Agriculture		Mining		Manufacturing		E-G-W	
γ_1	0.1339	(0.00)	0.3269	(0.00)	0.3859	(0.00)	0.2972	(0.00)
γ_2	..	..	0.2061	(0.00)	0.1299	(0.00)	0.1429	(0.00)
γ_3	0.8661	(0.00)	0.4542	(0.00)	0.3604	(0.00)	0.0197	(0.00)
γ_4	..	..	0.0128	(0.03)	0.1238	(0.00)	0.4623	(0.00)
γ_{11}	0.1159	(0.00)	0.2182	(0.00)	0.1063	(0.00)	0.1872	(0.00)
γ_{12}	..	..	-0.0616	(0.00)	-0.0689	(0.00)	-0.0314	(0.07)
γ_{13}	-0.1159	(0.00)	-0.1531	(0.00)	-0.0425	(0.03)	-0.0299	(0.00)
γ_{14}	..	..	-0.0035	(0.04)	0.0051	(0.76)	-0.1258	(0.00)
γ_{22}	..	..	0.1453	(0.00)	-0.0220	(0.18)	0.0056	(0.78)
γ_{23}	..	..	-0.0789	(0.00)	0.0236	(0.01)	0.0161	(0.14)
γ_{24}	..	..	-0.0048	(0.12)	0.0233	(0.05)	0.0096	(0.62)
γ_{33}	0.1159	(0.00)	0.2361	(0.00)	0.1230	(0.00)	0.0802	(0.00)
γ_{34}	..	..	-0.0041	(0.09)	-0.1040	(0.00)	-0.0664	(0.00)
γ_{44}	..	..	0.0124	(0.00)	0.0757	(0.00)	0.1826	(0.00)
γ_{1t}	0.0023	(0.00)	0.0000	(0.95)	0.0073	(0.00)	0.0026	(0.00)
γ_{2t}	..	..	0.0083	(0.00)	0.0015	(0.01)	0.0037	(0.00)
γ_{3t}	-0.0023	(0.00)	-0.0065	(0.00)	-0.0062	(0.00)	-0.0120	(0.00)
γ_{4t}	..	..	-0.0019	(0.00)	-0.0026	(0.00)	-0.0057	(0.00)
γ_{1K}	..	..	0.1645	(0.00)	..	..	0.1673	(0.00)
γ_{2K}	..	..	0.1924	(0.00)	..	..	0.2506	(0.00)
γ_{3K}	..	..	-0.3347	(0.00)	..	..	-0.4525	(0.00)
γ_{4K}	..	..	-0.0222	(0.00)	..	..	0.0346	(0.68)
R^2								
w_1	0.9650		0.9000		0.7627		0.8030	
w_2	..		0.9386		0.8368		0.7371	
w_3	..		0.7976		0.6053		0.8825	
w_4	..		..		..		..	
$\tilde{R}^2$	0.9969		1.0000		1.0000		1.0000	

Note: Values in parenthesis are the probabilities at which the corresponding coefficients are statistically significant.
Source: Author's estimations.

Appendix Table A7.1 (Continued) **Non-linear maximum likelihood parameter Estimates, fuel choice model**

Para-meters	Construction		Transport		Services	
γ_1	0.0042	(0.00)	0.0062	(0.00)	0.8842	(0.00)
γ_2	0.0029	(0.00)	0.0015	(0.00)	0.0659	(0.00)
γ_3	0.9929	(0.00)	0.9923	(0.00)	0.0483	(0.00)
γ_4	..	..	..	..	0.0016	(0.00)
γ_{11}	0.0014	(0.38)	0.0061	(0.00)	0.0798	(0.00)
γ_{12}	0.0041	(0.00)	0.0001	(0.76)	-0.0429	(0.00)
γ_{13}	-0.0055	(0.00)	-0.0062	(0.00)	-0.0394	(0.00)
γ_{14}	..	..	..	..	0.0025	(0.01)
γ_{22}	-0.0033	(0.00)	0.0007	(0.00)	0.0457	(0.00)
γ_{23}	-0.0008	(0.13)	-0.0008	(0.00)	-0.0013	(0.14)
γ_{24}	..	..	..	..	-0.0016	(0.01)
γ_{33}	-0.0063	(0.00)	-0.0070	(0.00)	0.0422	(0.00)
γ_{34}	..	..	..	..	-0.0016	(0.00)
γ_{44}	..	..	..	..	0.0007	(0.01)
γ_{1t}	-0.0000	(0.78)	0.0001	(0.04)	0.0040	(0.00)
γ_{2t}	0.0000	(0.09)	0.0002	(0.00)	0.0003	(0.01)
γ_{3t}	-0.0000	(0.83)	-0.0002	(0.00)	-0.0041	(0.00)
γ_{4t}	..	..	..	..	-0.0002	(0.00)
γ_{1K}	-0.0033	(0.20)	-0.0036	(0.11)	0.1570	(0.00)
γ_{2K}	0.0028	(0.00)	0.0037	(0.05)	0.0817	(0.00)
γ_{3K}	0.0005	(0.87)	-0.0001	(0.95)	-0.2353	(0.00)
γ_{4K}	..	..	..	..	-0.0034	(0.01)
R^2						
w_1	0.8583		0.9000		0.7960	
w_2	0.8175		0.9386		0.7695	
w_3	..		0.7976		0.7697	
w_4	..		..		..	
$\widetilde{R}^2$	0.9981		0.9995		1.0000	

Note: Values in parenthesis are the probabilities at which the corresponding coefficients are statistically significant.
Source: Author's estimations.

Appendix Table A7.2 **Non-linear maximum likelihood parameter estimates, aggregate choice model**

Parameters	Agriculture		Mining		Manufacturing	
α_0	5.2461	(0.00)	138.7400	(0.45)	49.5200	(0.00)
α_E	-0.0008	(0.05)	-2.9045	(0.00)	-0.0092	(0.54)
α_M	1.2782	(0.00)	..	..	4.6210	(0.00)
α_K	-3.5700	(0.00)	-1.2678	(0.00)	0.5228	(0.38)
α_{EE}	-0.0000	(1.00)	-0.0036	(0.69)	-0.1226	(0.00)
α_{EM}	0.0006	(0.00)	..	..	0.0309	(0.00)
α_{EK}	0.0009	(0.00)	0.0045	(0.30)	0.1480	(0.00)
α_{MM}	-0.0012	(0.00)	..	..	-0.2277	(0.00)
α_{MK}	-0.3194	(0.00)	..	..	-0.9033	(0.26)
α_{KK}	1.2095	(0.00)	0.4314	(0.00)	1.4104	(0.22)
$\alpha_{\dot{K}\dot{K}}$	37.6500	(0.00)	1.7268	(0.00)	152.8900	(0.00)
α_{0t}	-0.0803	(0.00)	0.4751	(0.28)	0.0020	(0.97)
α_{Et}	0.00003	(0.00)	0.0150	(0.26)	-0.0003	(0.07)
α_{Mt}	-0.0088	(0.01)	..	..	-0.0505	(0.05)
α_{Kt}	0.0317	(0.00)	-0.0201	(0.00)	-0.0177	(0.01)
ρ_E	..	..	0.9946	(0.00)	0.5719	(0.00)
ρ_M	..	..	..	..	0.9793	(0.00)
ρ_L	..	..	1.0028	(0.00)	1.000	(0.00)
ρ_I	..	..	0.9600	(0.00)	0.8865	(0.00)
m^*	0.1364		0.4326		0.0372	
R^2						
E/Y	0.9060		0.7923		0.9639	
M/Y	0.2067		..		0.6491	
L/Y	0.1055		0.6567		0.9953	
I/Y	0.0464		0.1032		0.2733	
$\tilde{R}^2$	0.9963		0.9996		1.0000	

Note: Values in parenthesis are the probabilities at which the corresponding coefficients are statistically significant.
Source: Author's estimations.

Appendix Table A7.2 (continued) **Non-linear maximum likelihood parameter estimates, aggregate choice model**

Para-meters	E-G-W		Construction		Transport		Services	
α_0	-10.2180	(0.11)	-0.0337	(0.87)	-606.74	(0.00)	5.1431	(0.00)
α_E	-2.6212	(0.00)	0.0123	(0.00)	0.4870	(0.00)	-0.6314	(0.00)
α_M	..	..	0.6973	(0.00)	..	..	..	..
α_K	-4.2771	(0.00)	0.7820	(0.03)	-4.7693	(0.00)	-4.3565	(0.00)
α_{EE}	-0.1060	(0.21)	-0.0068	(0.00)	-0.0143	(0.03)	-0.0010	(0.25)
α_{EM}	..	..	0.0045	(0.09)	..	..	..	..
α_{EK}	0.0044	(0.61)	0.0255	(0.00)	0.0421	(0.00)	0.0024	(0.00)
α_{MM}	..	..	-0.0278	(0.54)	..	..	..	..
α_{MK}	..	..	-1.076	(0.00)	..	..	..	..
α_{KK}	0.6409	(0.00)	0.9722	(0.28)	1.3083	(0.00)	1.5996	(0.00)
$\alpha_{\dot{K}\dot{K}}$	-	(0.00)	419.94	(0.00)	26.5160	(0.00)	18.6420	(0.00)
α_{0t}	3.3011	(0.10)	0.0058	(0.35)	-1.3159	(0.01)	0.0942	(0.03)
α_{Et}	-0.2079	(0.58)	-0.0002	(0.12)	-0.0050	(0.00)	0.0033	(0.00)
α_{Mt}	..	..	0.0057	(0.01)	..	..	..	..
α_{Kt}	0.0087	(0.03)	-0.0228	(0.11)	0.0428	(0.04)	-0.0261	(0.01)
ρ_E	0.9977	(0.00)	0.7380	(0.00)	0.5403	(0.00)	0.9941	(0.00)
ρ_M	..	..	0.3125	(0.03)	..	..	..	..
ρ_L	1.0022	(0.00)	0.8223	(0.00)	1.0018	(0.00)	0.9815	(0.00)
ρ_I	0.9705	(0.00)	0.2009	(0.12)	0.9689	(0.00)	0.9763	(0.00)
m^*	0.4126		0.0195		0.1878		0.2215	
R^2								
E/Y	0.8540		0.5716		0.9977		0.9265	
M/Y	..		0.6455		..		..	
L/Y	0.9292		0.8158		0.9109		0.7421	
I/Y	0.4960		0.1067		0.5284		0.2097	
$\tilde{R}^2$	1.0000		1.0000		1.0000		1.0000	

Note: Values in parenthesis are the probabilities at which the corresponding coefficients are statistically significant.
Source: Author's estimations.

Appendix Table A7.3 **Agriculture: short and long-run elasticities, 1998**

Aggregate choice model

Quantity	Price			
	Energy	Materials	Labour	Capital
Energy				
Short-run	-0.0000	0.3135	-0.3135	..
Long-run	-0.0004	0.4393	-0.0450	-0.3940
Materials				
Short-run	0.0012	-0.0024	0.0012	..
Long-run	0.0017	-0.1741	-0.3650	0.5373
Labour				
Short-run	-0.0056	0.0056	0.0000	..
Long-run	0.0003	-2.0562	-4.4055	6.4643
Capital				
Long-run	-0.0006	0.2143	0.4573	-0.6710

Fuel choice model

Quantity	Price			
	Electricity	Gas	Oil	Coal
Electricity				
E constant	-0.0000	..	0.0000	..
Short-run	-0.0000	..	0.0000	..
Long-run	-0.0001	..	-0.0003	..
Gas				
E constant	..	..	..	..
Short-run	..	..	..	..
Long-run	..	..	..	..
Oil				
E constant	0.0000	..	-0.0000	..
Short-run	0.0000	..	-0.0000	..
Long-run	-0.0001	..	-0.0003	..
Coal				
E constant	..	..	..	..
Short-run	..	..	..	..
Long-run	..	..	..	..

Note: E = energy.
Source: Author's estimations.

Appendix Table A7.4 **Mining: short and long-run elasticities, 1998**

Aggregate choice model

Quantity	Price			
	Energy	Materials	Labour	Capital
Energy				
Short-run	-0.0338	..	0.0338	..
Long-run	-0.0342	..	0.1315	-0.0973
Materials				
Short-run	..	..	..	..
Long-run	..	..	..	..
Labour				
Short-run	0.0135	..	-0.0135	..
Long-run	0.0310	..	-3.8967	3.8657
Capital				
Long-run	-0.0028	..	0.6277	-0.6248

Fuel choice model

Quantity	Price			
	Electricity	Gas	Oil	Coal
Electricity				
E constant	-0.0056	0.0177	-0.0142	0.0021
Short-run	-0.0167	0.0107	-0.0295	0.0016
Long-run	-0.0172	0.0102	-0.0302	0.0012
Gas				
E constant	0.0280	-0.0890	0.0714	-0.0104
Short-run	0.0170	-0.0960	0.0560	-0.0108
Long-run	0.0163	-0.0966	0.0553	-0.0113
Oil				
E constant	-0.0102	0.0324	-0.0259	0.0038
Short-run	-0.0212	0.0254	-0.0413	0.0033
Long-run	-0.0204	0.0263	-0.0405	0.0043
Coal				
E constant	0.0524	-0.1665	0.1334	-0.0194
Short-run	0.0413	-0.1735	0.1181	-0.0200
Long-run	0.0413	-0.1735	0.1180	-0.0197

Note: E = energy.
Source: Author's estimations.

Appendix Table A7.5 **Manufacturing: short and long-run elasticities, 1998**

Aggregate choice model

Quantity	Price			
	Energy	Materials	Labour	Capital
Energy				
Short-run	-0.3213	0.6614	-0.3401	..
Long-run	-0.6536	2.6893	0.2093	-2.2449
Materials				
Short-run	0.0449	-0.3571	0.3085	..
Long-run	0.1972	-1.2645	0.0627	1.0045
Labour				
Short-run	-0.0879	1.0873	-0.9995	..
Long-run	-0.2738	2.2222	-0.6920	-1.2563
Capital				
Long-run	-0.3034	1.8517	0.5016	-2.0499

Fuel choice model

Quantity	Price			
	Electricity	Gas	Oil	Coal
Electricity				
E constant	-0.3385	-0.0487	0.2502	0.1371
Short-run	-0.4626	-0.0939	0.1344	0.0973
Long-run	-0.5908	-0.1335	0.0146	0.0561
Gas				
E constant	-0.1446	-0.7005	0.5422	0.3029
Short-run	-0.2686	-0.7422	0.4264	0.2631
Long-run	-0.3969	-0.7854	0.3067	0.2220
Oil				
E constant	0.2679	0.1954	-0.2984	-0.1649
Short-run	0.1439	0.1537	0.4142	-0.2047
Long-run	0.0157	0.1105	-0.5340	-0.2458
Coal				
E constant	0.4271	0.3176	-0.4797	-0.2650
Short-run	0.3031	0.2759	-0.5955	-0.3048
Long-run	0.1749	0.2328	-0.7153	-0.3460

Note: E = energy.
Source: Author's estimations.

Appendix Table A7.6 **E-G-W: short and long-run elasticities, 1998**

Aggregate choice model

Quantity	Price			
	Energy	Materials	Labour	Capital
Energy				
Short-run	-0.0395	..	0.0395	..
Long-run	-0.0396	..	0.0654	-0.0258
Materials				
Short-run	..	..	..	..
Long-run	..	..	..	..
Labour				
Short-run	0.0656	..	-0.0656	
Long-run	0.0746	..	-2.0980	2.2034
Capital				
Long-run	-0.0014	..	0.3174	-0.3160

Fuel choice model

Quantity	Price			
	Electricity	Gas	Oil	Coal
Electricity				
E constant	-0.0731	0.0373	-0.0031	0.0389
Short-run	-0.0848	0.0317	-0.0070	0.0206
Long-run	-0.0851	0.0314	-0.0072	0.0203
Gas				
E constant	0.0776	-0.8177	0.2104	0.5297
Short-run	0.0659	-0.8233	0.2066	0.5114
Long-run	0.0655	-0.8237	0.2063	0.5110
Oil				
E constant	-0.0095	0.3080	-0.0811	-0.2174
Short-run	-0.0212	0.3024	-0.0850	-0.2357
Long-run	-0.0206	0.3030	-0.0843	-0.2351
Coal				
E constant	0.0250	0.1637	-0.0459	-0.1428
Short-run	0.0133	0.1580	-0.0498	-0.1610
Long-run	0.0132	0.1580	-0.0498	-0.1611

Note: E = energy.
Source: Author's estimations.

Appendix Table A7.7 **Construction: short and long-run elasticities, 1998**

Aggregate choice model

Quantity	Price			
	Energy	Materials	Labour	Capital
Energy				
Short-run	-0.6093	0.4021	0.2072	..
Long-run	-0.6694	2.9365	0.0875	-2.3547
Materials				
Short-run	0.0084	-0.0524	0.0439	..
Long-run	0.0616	-2.2950	0.1499	2.0835
Labour				
Short-run	0.1029	0.1040	-0.1143	..
Long-run	-0.0085	0.8978	-0.1518	-0.7375
Capital				
Long-run	-0.0958	-0.1911	4.0444	-3.7575

Fuel choice model

Quantity	Price			
	Electricity	Gas	Oil	Coal
Electricity				
E constant	-0.6519	0.9809	-0.3290	..
Short-run	-0.6545	0.9791	-0.9340	..
Long-run	-0.6544	0.9793	-0.9933	..
Gas				
E constant	1.4304	-2.1522	0.7218	..
Short-run	1.4279	-2.1539	0.1168	..
Long-run	1.4274	-2.1544	0.0568	..
Oil				
E constant	-0.0014	0.0021	-0.0007	..
Short-run	-0.0039	0.0003	-0.6057	..
Long-run	-0.0042	0.0001	-0.6654	..
Coal				
E constant	..	..	..	..
Short-run	..	..	..	..
Long-run	..	..	..	..

Note: E = energy.
Source: Author's estimations.

Appendix Table A7.8 **Transport, storage and communication: short and long-run elasticities, 1998**

Aggregate choice model

Quantity	Price			
	Energy	Materials	Labour	Capital
Energy				
Short-run	-0.0390	..	0.0390	..
Long-run	-0.0427	..	0.1307	-0.0880
Materials				
Short-run	..	..	..	..
Long-run	..	..	..	..
Labour				
Short-run	0.0537	..	-0.0537	..
Long-run	0.1049	..	-1.3218	1.2168
Capital				
Long-run	-0.0158	..	0.3893	-0.3735

Fuel choice model

Quantity	Price			
	Electricity	Gas	Oil	Coal
Electricity				
E constant	-0.0031	-0.0095	0.0073	0.0053
Short-run	-0.0034	-0.0096	-0.0315	0.0054
Long-run	-0.0073	-0.0135	-0.0391	0.0015
Gas				
E constant	-0.0350	-0.4312	-0.3192	0.7855
Short-run	-0.0353	-0.4313	-0.3580	0.7856
Long-run	-0.0392	-0.4351	-0.3655	0.7818
Oil				
E constant	0.0001	-0.0006	-0.0012	0.0017
Short-run	-0.0002	-0.0007	-0.0400	0.0018
Long-run	-0.0106	-0.0110	-0.0540	-0.0085
Coal				
E constant	-0.0148	-0.5937	-0.7036	1.3121
Short-run	-0.0150	-0.5938	-0.7424	1.3122
Long-run	0.0030	-0.5757	-0.7280	1.3303

Note: E = energy.
Source: Author's estimations.

Appendix Table A7.9 **Services: short and long-run elasticities, 1998**

Aggregate choice model

Quantity	Price			
	Energy	Materials	Labour	Capital
Energy				
Short-run	-0.0566	..	0.0566	..
Long-run	-0.0568	..	0.1445	-0.0877
Materials				
Short-run	..	..	..	..
Long-run	..	..	..	..
Labour				
Short-run	0.0017	..	-0.0017	
Long-run	0.0025	..	-0.3451	0.3426
Capital				
Long-run	-0.0005	..	0.1987	-0.1981

Fuel choice model

Quantity	Price			
	Electricity	Gas	Oil	Coal
Electricity				
E constant	-0.0256	0.0174	0.0038	0.0044
Short-run	-0.0757	0.0137	0.0010	0.0044
Long-run	-0.0759	0.0136	0.0010	0.0043
Gas				
E constant	0.2334	-0.2399	0.0293	-0.0228
Short-run	0.1834	-0.2436	0.0265	-0.0229
Long-run	0.1832	-0.2437	0.0265	-0.0229
Oil				
E constant	0.0692	0.0399	-0.0781	-0.0309
Short-run	0.0191	0.0361	-0.0809	-0.0310
Long-run	0.0190	0.0363	-0.0808	-0.0309
Coal				
E constant	2.3928	-0.9137	-0.9089	-0.5702
Short-run	2.3427	-0.9174	-0.9116	-0.5703
Long-run	2.3426	-0.9174	-0.9116	-0.5703

Note: E = energy.
Source: Author's estimations.

8

Where do the energy substitution possibilities lie?

Synopsis

The structure of energy demand by sector, estimated elsewhere in this research, is closely examined with a view to identifying the energy conservation potential (including inter-fuel substitution opportunities) in major energy consuming sectors/industries. While the demand for aggregate energy input in the mining, power and transport sectors is essentially independent of energy prices, some inter-fuel substitution possibilities exist in mining and in power, largely in private power plants. In contrast, energy demand in manufacturing in aggregate is not only significantly own-price sensitive but also strong substitution opportunities exist among the major fuels, notably gas and coal. An industry-level analysis of the fuel structure, however, finds very little evidence for inter-fuel substitution possibilities in iron and steel and basic non-ferrous metals – two major energy-consuming industries – implying that such possibilities are probably exaggerated in the aggregate analysis of manufacturing. The application of a carbon tax, therefore, is not likely to significantly reduce the energy sector CO_2 emissions.

8.1 Introduction

Australia is bound, according to the Kyoto Protocol[1] to the United Nations Framework Convention on Climate Change (UNFCCC), signed in Kyoto in December 1997, to limit its GHG emissions to 8 per cent above their 1990 level in the first commitment period, 2008-12. In order to achieve this target, Australia may have to cut GHG emissions by about 22 per cent in 2010 relative to the business-as-usual emissions in 2010.[2] As the likelihood of a major technological breakthrough[3] during this period is small, most of this abatement is likely to be achieved through demand management – energy conservation, including switching from more carbon-intensive fuels to relatively environment-friendly fuels such as gas.[4] From a policy perspective, therefore, a thorough understanding of energy use behaviour – energy substitution generally and, more importantly, inter-fuel substitution in different sectors (industrial, commercial and residential) is of crucial significance.

The previous two chapters modelled the structure of energy demand in the industrial and commercial sectors using flexible and/or dynamic demand systems. Using the static translog system, Chapter 6 estimated the fuel structure by dividing the non-residential economy into 37 industries and categorising total energy use into electricity, gas, oil and coal. Total energy demand in that analysis was taken as an exogenous variable, as at the level of detail sought in the study, data on other inputs could not be obtained. Chapter 7 endogenised the demand for energy along with that of other inputs by compromising at the level of industrial detail; the non-residential economy was divided into seven sectors. Earlier, in Chapters 3 and 4, consumer preferences were modelled with a view to explaining energy use behaviour in the household sector.

The estimated energy demand structure, especially in Chapters 6 and 7, could only be overviewed due to the enormous number of parameters involved. However, in order to identify energy substitution and the substitution potential between different energy sources in various industries/sectors, a closer look at these structures – the main aim in this chapter – is required. The intention is to first analyse such opportunities at an aggregate level such as manufacturing and electricity, gas and water – the picture painted in Chapter 7. Then, in order to further pinpoint the location of such potentials and, more importantly, to see whether the aggregate picture is not a distorted one because of aggregation across highly different industries – for instance, manufacturing – the corresponding sub-sector level inter-fuel elasticities are brought into the discussion.

The analysis focuses on major energy consuming sectors including manufacturing, electricity, gas and water, and transport, storage and communication. The residential and mining sectors with shares of 6.8 per cent and 5 per cent respectively in gross national energy consumption in 1998 are also included. Within manufacturing, fuel conservation opportunities are explored in six major energy consuming industries namely iron and steel, basic non-ferrous metals, petroleum refining, basic chemicals, wood, paper and printing, and cement, lime, plaster and concrete. These six industries accounted for approximately 80 per cent of the sector's gross energy consumption between 1974 and 1995. In electricity, gas and water, the public and private electricity generation sub-sectors are further investigated.

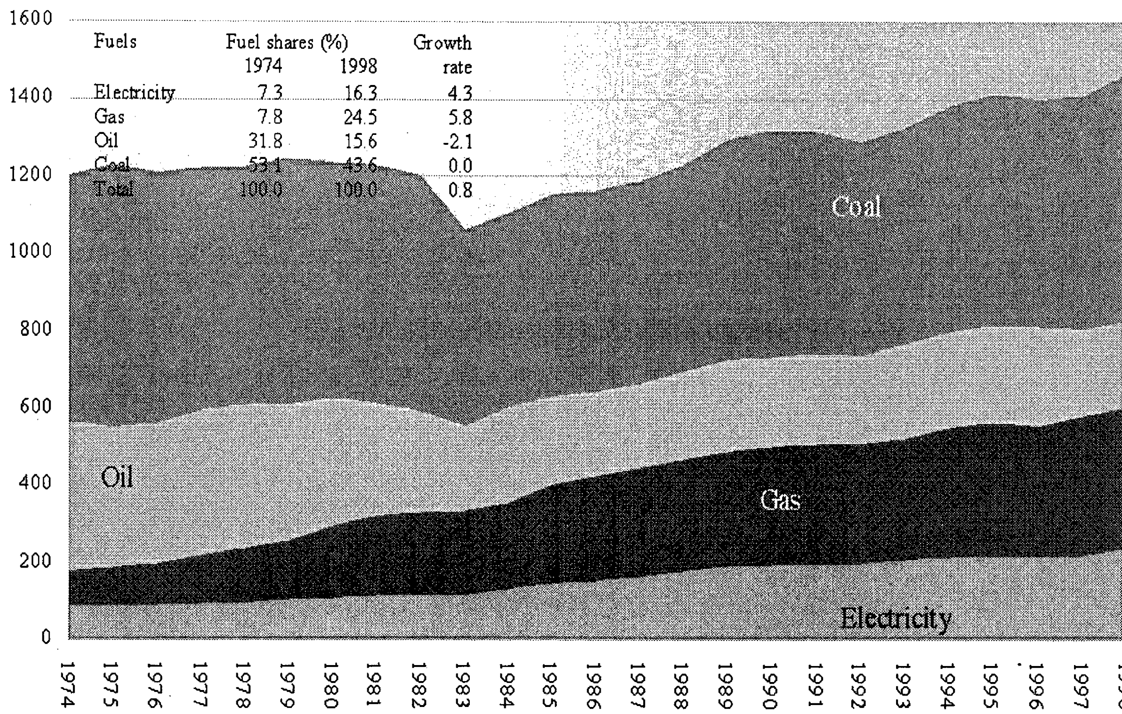
The rest of the chapter is organised as follows. Section 8.2 briefly discusses the manufacturing sector's energy consumption, followed by an analysis of the estimated energy demand structure. The same procedure is adopted for each of the six manufacturing industries in separate subsections. The energy conservation potential in the largest energy-consuming sector – electricity, gas and water – is analysed in Section 8.3. The following three sections examine the transport, mining and residential sectors. The chapter is summarised in Section 8.7.

8.2 Manufacturing

Energy use in manufacturing, the largest energy consuming sector until 1983 and the second largest since 1984, increased from 1.2 EJ in 1974 to 1.5 EJ in 1998, growing at the modest rate of 0.8 per cent a year (Figure 8.1). This slow growth is largely because of a 40 per cent reduction in oil consumption, the second largest fuel source in the 1970s, and near stagnant coal consumption – the largest fuel source over the entire 25-year period. Electricity and gas use by the industry, on the other hand, grew rapidly; electricity consumption grew at 4.3 per cent and that of gas at 5.8 per cent a year.

As a result of these different growth rates, the sector's fuel structure changed dramatically over the 25 years to 1998. The oil share in 1998, for instance, was one-half of its pre-oil crisis level. There was a relatively less dramatic reduction in the industry's dependence on coal, as its share declined from 53.1 per cent to 43.6 per cent over the 25-year period. The combined share of electricity and gas, in contrast, increased to more than 40 per cent in 1998 from about 15 per cent in 1974, owing to a 2.7-fold increase in electricity and 3.8-fold jump in gas consumption. The rapid increase in the gas share in this sector was in large part because of the substitution of natural gas for oil in stationary appliances such as boilers and kilns. The increased electricity share in the fuel mix is largely attributable to the impressive growth in the aluminum industry (Bush *et al.* 1999:32).

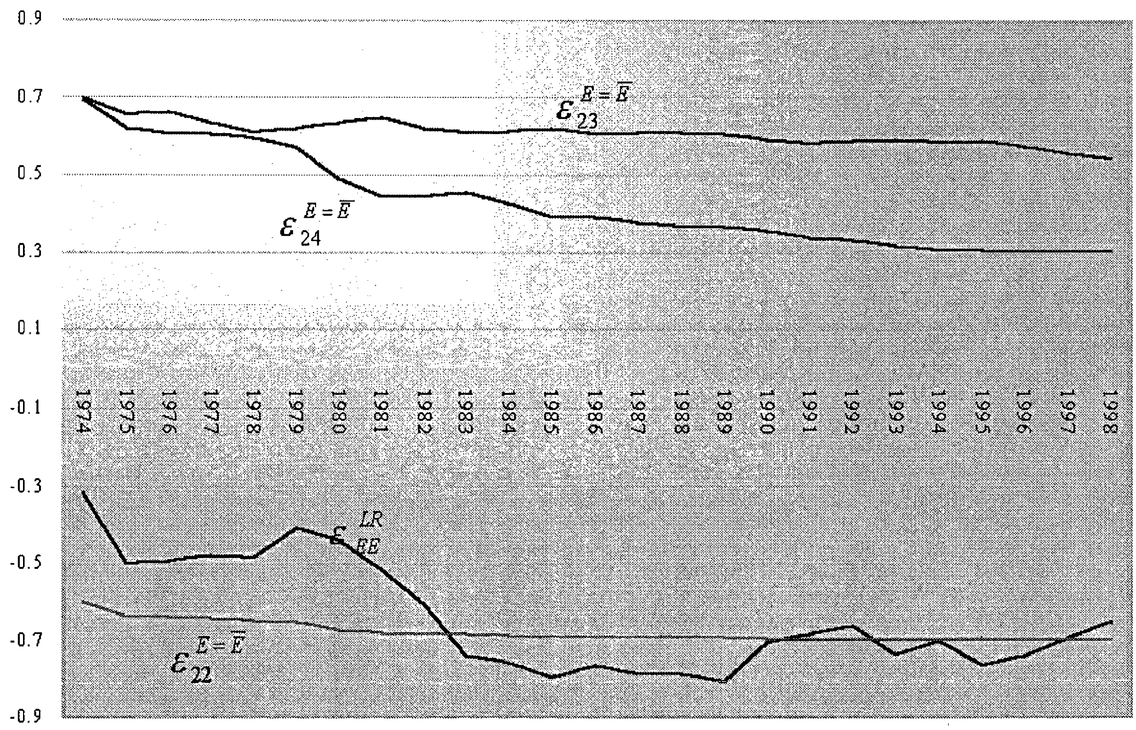
Figure 8.1 **Manufacturing energy consumption by fuel** (peta joules)



Source: Bush *et al.* 1999. *Australian Energy: market developments and projections to 2014-15*, Research Report No. 99.4, Australian Bureau of Agricultural and Resource Economics, Canberra.

The long-run energy demand elasticity (ε_{EE}^{LR}) is plotted in Figure 8.2. Furthermore, in order to get an impression of the inter-fuel substitution potential between the main fuels, the own inter-fuel price elasticity of gas ($\varepsilon_{22}^{E=\bar{E}}$) along with two of its cross-price elasticities – with respect to oil ($\varepsilon_{23}^{E=\bar{E}}$) and coal ($\varepsilon_{24}^{E=\bar{E}}$) prices – are also depicted in Figure 8.2. Energy demand in the industry is considerably responsive to own-price movements. The long-run elasticity of aggregate energy demand increased from -0.32 in 1974 to -0.81 in the late 1980s. In a reversal of trend, the elasticity has been declining, in a fluctuating manner, since the early 1990s; in 1998 it is estimated at -0.65. Not only is total energy demand considerably price sensitive but also there exist significant substitution opportunities between gas-oil and gas-coal. The own-price elasticity of gas has increased from -0.60 in 1974 to -0.70 in 1998. Similarly, the cross-price elasticities with respect to oil and coal are very high, reflecting the existence of significant substitution possibilities away from coal and oil to gas. Other elasticities, not reported in this figure, also show considerable flexibility. Electricity-gas and oil-coal tend to be complementary fuels, whereas all other fuel pairs are substitutes. Thus, a carbon tax is likely to reduce total energy demand by the sector and considerably change the fuel mix in favour of gas.

Figure 8.2 **Manufacturing energy demand elasticities**



Source: Author's estimations.

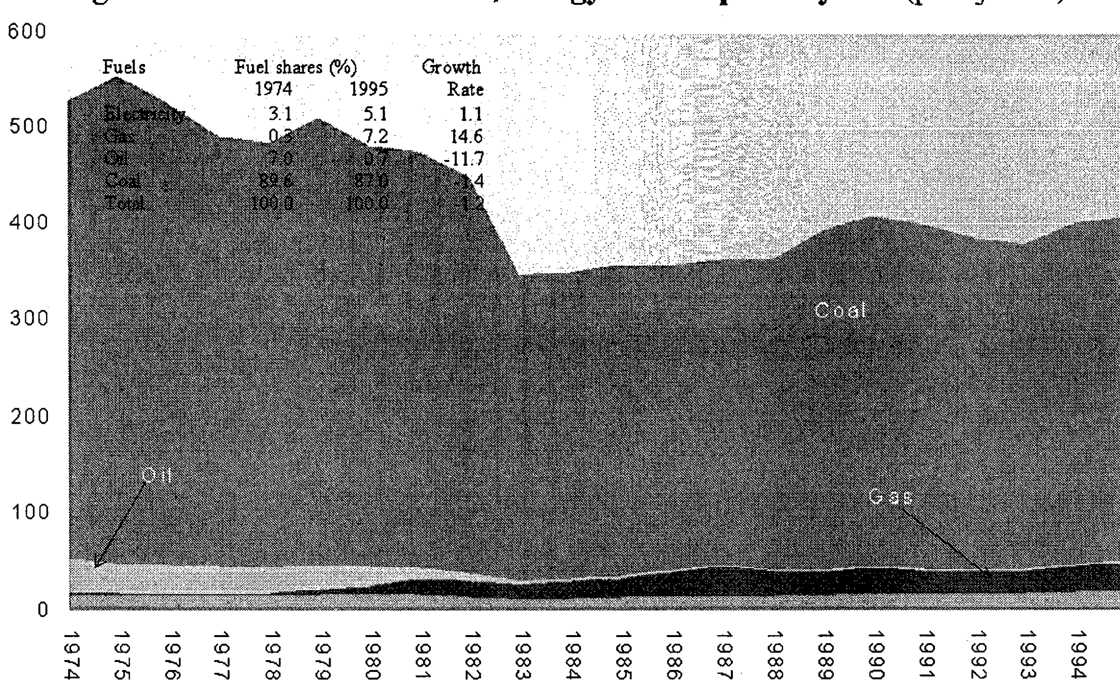
However, it is highly unlikely that the individual industries included in manufacturing follow energy use patterns similar to those of aggregate manufacturing. It is also possible that the estimated substitution opportunities are exaggerated due to an aggregation across a heterogeneous set of industries. In order to investigate this, the inter-fuel price elasticities estimated in Chapter 6 are employed. In Chapter 6 the manufacturing sector was divided into 23 sub-sectors and inter-fuel elasticities were computed for each of the 23 industries. As mentioned above, not all manufacturing industries are analysed here; rather, the six major energy consuming industries, accounting for nearly 80 per cent of the sector's gross energy consumption between 1974 and 1995, are chosen for the extended treatment. In each of the following subsections, the industry's energy structure is briefly discussed before moving on to analysing the substitution elasticities.

8.2.1 Iron and steel

Iron and steel is the largest energy consuming industry in the manufacturing sector. In 1974 the industry used more than 527 PJ, accounting for about 44 per cent of the sector's gross energy use. However, over the ten-year period to 1983 energy consumption in the industry fell substantially – by about 34 per cent to 347.9 PJ – caused by a sharp decline in the world demand for steel, especially between 1979 and 1983.[5] During this three-year period, international steel consumption fell by 19 per cent and in Australia by more than one-quarter. In response to falling demand, BHP Steel reduced its capacity by one-third to six million tonnes in mid-1983 (Prescott and McLeod 1999:1). Since 1983 energy consumption in the industry has increased, in a fluctuating fashion, to 407.6 PJ in 1995. As a result of the major restructuring and the consequent downsizing, the industry's share in the manufacturing sector's gross energy consumption fell by more than 15 percentage points to 28.8 per cent in 1995.

In the iron and steel industry, energy is predominantly sourced from coal, namely black coal and coke; nearly 90 per cent of total energy requirements were met from this fuel source in 1974 (Figure 8.3). The coal share fell steadily to about 87 per cent in the 22-year period to 1995. The consumption of oil – the second major energy source in 1974 – fell very sharply from 36.7 PJ to a mere 2.71 PJ between 1974 and 1995, a 93 per cent decline. In a reversal of trend, the gas share increased from 0.32 per cent to more than 7 per cent over the same period, nearly completely replacing oil.

Figure 8.3 **Iron and steel, energy consumption by fuel** (peta joules)



Source: Bush *et al.* 1999. *Australian Energy: market developments and projections to 2014-15*, Research Report No. 99.4, Australian Bureau of Agricultural and Resource Economics, Canberra.

Given the sheer size of coal consumption, the fuel price elasticities involving coal are of crucial significance from the viewpoint of energy conservation. The nature of the relationship between gas and oil, as implied by the inter-fuel price elasticities, is also of interest, as apparently gas has almost fully replaced oil in the industry during the 22-year period to 1995.

The inter-fuel price elasticities, along with the corresponding t-values, are reported in Table 8.1 for selected years. In the lower panel of the table are the price elasticities of coal with respect to different fuel prices. The own-price elasticity of coal in 1995 – the year around which the concavity restrictions are imposed – although negatively signed is insignificant. In the previous years reported in this table, the elasticity is wrongly signed but not significant at the 5 per cent level of significance, implying that coal consumption in the iron and steel industry has not been responsive to own-price movements. Coal is complementary to electricity but a substitute for oil. The estimated coal-oil relationship should, however, be taken with caution, as the t-scores are low since the mid-1980s. The rapid increase in oil prices during the late 1970s and the early 1980s might have caused some switching from oil to coal. However, it is more likely that over this period oil was replaced predominantly by gas, as the two fuels are strong substitutes; the cross-price elasticity of gas with respect to oil price is very high – varying between 13.4 in 1975 and 0.48 in 1995.

The insensitivity of coal demand and the limited substitution potential between coal and other fuels is not entirely surprising given the long working life of iron and steel making plants (typically more than 20 years) and the very limited choice between alternative fuels in an established facility. Furthermore, there was apparently no incentive to utilise the limited flexibility in fuel choice because coal prices have been very stable over the years.

Oil and gas are significantly own-price sensitive. This is especially true in the case of oil, as its demand is not only own-price elastic but also the price sensitivity has increased over the years. In contrast, the own-price elasticity of electricity is not only (mostly) wrongly signed but also highly significant. The concavity restrictions in 1995 corrected the sign but at the expense of significance; the t-score is only 0.28 for the year. An increase in the relative price of coal caused by, say, the imposition of a carbon tax is not expected to reduce coal consumption in the near future, as the coal elasticity is essentially zero. However, such a tax, if applied independently, may erode Australia's international competitiveness and, therefore, reduce the demand for Australian steel. In such a circumstance, the demand for energy, including coal, will decline, following a reduction in steel production.

Table 8.1 **Iron and steel, inter-fuel price elasticities for selected years**

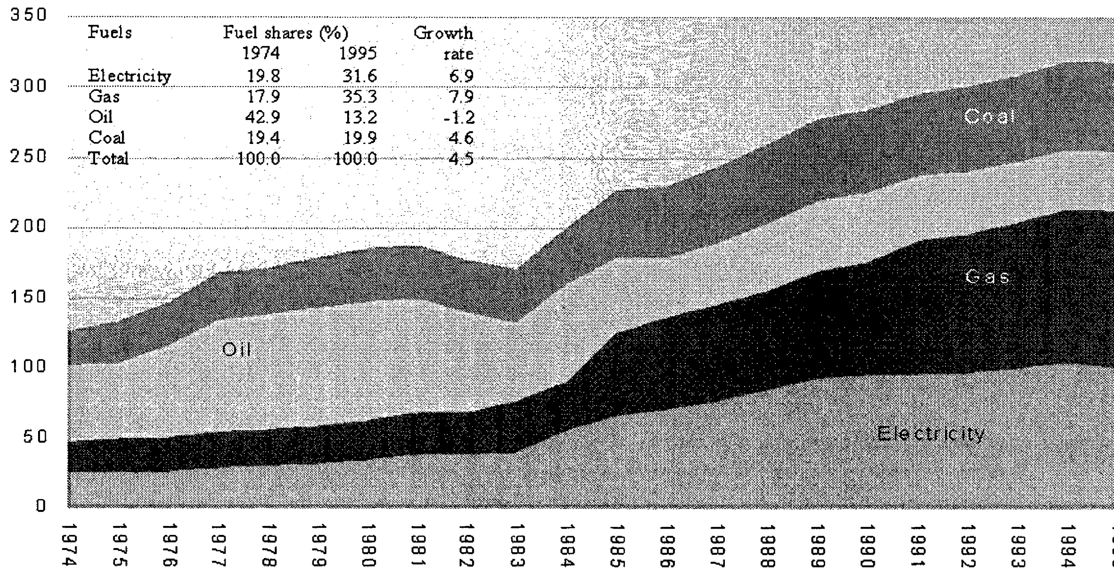
Years	value	t-score	value	t-score	value	t-score	value	t-score
	Electricity							
	ε_{11}		ε_{12}		ε_{13}		ε_{14}	
1975	0.537	7.458	-0.069	0.702	0.026	0.618	-0.494	10.381
1980	0.353	5.746	-0.032	0.386	0.005	0.133	-0.326	8.009
1985	0.236	4.330	0.002	0.021	-0.005	0.149	-0.232	6.450
1990	0.099	2.159	0.022	0.362	-0.013	0.469	-0.109	3.584
1995	-0.010	0.276	0.045	0.868	-0.019	0.854	-0.015	0.598
	Gas							
	ε_{21}		ε_{22}		ε_{23}		ε_{24}	
1975	-3.093	0.702	4.437	0.939	13.428	4.033	-14.773	2.724
1980	-0.170	0.386	-0.428	0.905	1.393	4.184	-0.796	1.467
1985	0.005	0.021	-0.662	2.701	0.735	4.257	-0.078	0.277
1990	0.068	0.362	-0.701	3.494	0.594	4.202	0.039	0.170
1995	0.134	0.868	-0.728	4.407	0.480	4.130	0.114	0.599
	Oil							
	ε_{31}		ε_{32}		ε_{33}		ε_{34}	
1975	0.038	0.618	0.431	4.033	-1.173	6.664	0.704	4.648
1980	0.012	0.133	0.680	4.184	-1.341	5.006	0.649	2.815
1985	-0.019	0.149	0.945	4.257	-1.504	4.108	0.578	1.835
1990	-0.094	0.469	1.457	4.202	-1.827	3.195	0.464	0.943
1995	-0.330	0.854	2.761	4.130	-2.634	2.388	0.202	0.213
	Coal							
	ε_{41}		ε_{42}		ε_{43}		ε_{44}	
1975	-0.083	10.381	-0.055	2.724	0.082	4.648	0.056	1.840
1980	-0.065	8.009	-0.030	1.467	0.050	2.815	0.045	1.445
1985	-0.055	6.450	-0.006	0.277	0.034	1.835	0.026	0.815
1990	-0.032	3.584	0.004	0.170	0.018	0.943	0.010	0.283
1995	-0.006	0.598	0.014	0.599	0.004	0.213	-0.013	0.362

Notes: Theoretical values: 1 per cent = 2.66, 5 per cent = 2.0, 10 per cent = 1.67. The significance of the elasticities is not specified, mainly to leave the table simple.
Source: Author's estimations.

8.2.2 Basic non-ferrous metals

Unlike iron and steel, basic non-ferrous metals – the second largest energy consuming industry in manufacturing – experienced a 2.5-fold increase in total energy use to 317.5 PJ in 1995, an average growth rate of 4.5 per cent a year (Figure 8.4). As a result of this rapid increase in energy use, the industry's share in the manufacturing sector's gross energy consumption rose from more than 10 per cent in 1974 to above 22 per cent in 1995. Another striking difference between iron and steel and non-ferrous metals is that the energy profile in the latter industry is fairly diverse. In 1974, the shares of the different fuel sources varied between 17.9 per cent (for gas) to 42.9 per cent (for coal). However, during the following period of more than two decades, electricity and gas consumption experienced respectively 4 and 5-fold increases, whereas oil use fell by almost 22 per cent, resulting in a major restructuring in the fuel composition. As a consequence, the electricity and gas shares increased to 31.6 per cent and 35.3 per cent respectively and that of oil shrank to 13.2 per cent – an almost 30-percentage point trimming in the oil share. Coal consumption showed a remarkable resilience in the face of this major shake-up as its share remained more or less stable around at 20 per cent.

Figure 8.4 **Basic non-ferrous metals, energy consumption by fuel** (peta joules)



Source: Bush *et al.* 1999. ***Australian Energy: market developments and projections to 2014-15***, Research Report No. 99.4, Australian Bureau of Agricultural and Resource Economics, Canberra.

Given the relatively diverse energy mix and the massive restructuring in the fuel mix, it is interesting to see if these changing patterns can be explained with the help of inter-fuel price elasticities. The price elasticities for five years are reported in Table 8.2. The demand for electricity and coal has been fairly price sensitive; the coal demand elasticity, for instance, has varied between -0.54 in 1975 and -0.32 in 1995. The electricity elasticity has been fairly similar with a range of -0.29 to -0.48.

Also, the demand for oil – the biggest fuel source in the 1970s, with a share of 42.9 per cent in 1974 – is considerably (own) price responsive up until 1990; in 1995 the oil demand elasticity is not only very small but also insignificant, probably due to the concavity restrictions. The gas demand elasticity is positive for the 1970s and the 1980s but negative for the subsequent three years, although insignificant in all five years. As far as the cross-price elasticities are concerned, electricity-oil and electricity-coal are significant substitutes. In contrast, gas-oil, gas-coal and oil-coal tend to be complements. The cross-price elasticities between electricity and gas are positive but insignificant for most years.

Table 8.2 **Basic non-ferrous metals, inter-fuel price elasticities for selected years**

Years	value	t-score	value	t-score	value	t-score	value	t-score
	Electricity							
	ε_{11}		ε_{12}		ε_{13}		ε_{14}	
1975	-0.475	3.23	0.058	0.54	0.293	5.85	0.124	2.53
1980	-0.440	3.28	0.048	0.49	0.280	6.12	0.112	2.52
1985	-0.396	3.26	0.084	0.95	0.216	5.23	0.096	2.39
1990	-0.345	3.15	0.107	1.35	0.151	4.05	0.087	2.39
1995	-0.292	2.93	0.137	1.90	0.077	2.28	0.078	2.37
	Gas							
	ε_{21}		ε_{22}		ε_{23}		ε_{24}	
1975	0.274	0.54	0.092	0.28	-0.109	1.17	-0.257	1.56
1980	0.289	0.49	0.242	0.63	-0.213	1.97	-0.318	1.66
1985	0.396	0.95	-0.061	0.23	-0.117	1.52	-0.219	1.60
1990	0.475	1.35	-0.169	0.74	-0.124	1.92	-0.181	1.57
1995	0.554	1.90	-0.259	1.36	-0.147	2.71	-0.148	1.54
	Oil							
	ε_{31}		ε_{32}		ε_{33}		ε_{34}	
1975	0.327	5.85	-0.026	1.17	-0.323	7.52	0.022	1.95
1980	0.363	6.12	-0.046	1.97	-0.329	7.22	0.012	0.99
1985	0.385	5.23	-0.044	1.52	-0.329	5.81	-0.012	0.83
1990	0.394	4.05	-0.073	1.92	-0.282	3.78	-0.039	1.97
1995	0.344	2.28	-0.161	2.71	-0.091	0.78	-0.092	3.02
	Coal							
	ε_{41}		ε_{42}		ε_{43}		ε_{44}	
1975	0.757	2.53	-0.334	1.56	0.121	1.95	-0.544	5.36
1980	0.835	2.52	-0.394	1.66	0.068	0.99	-0.508	4.51
1985	0.960	2.39	-0.461	1.60	-0.069	0.83	-0.431	3.16
1990	1.063	2.39	-0.502	1.57	-0.181	1.97	-0.380	2.52
1995	1.180	2.37	-0.552	1.54	-0.312	3.02	-0.316	1.86

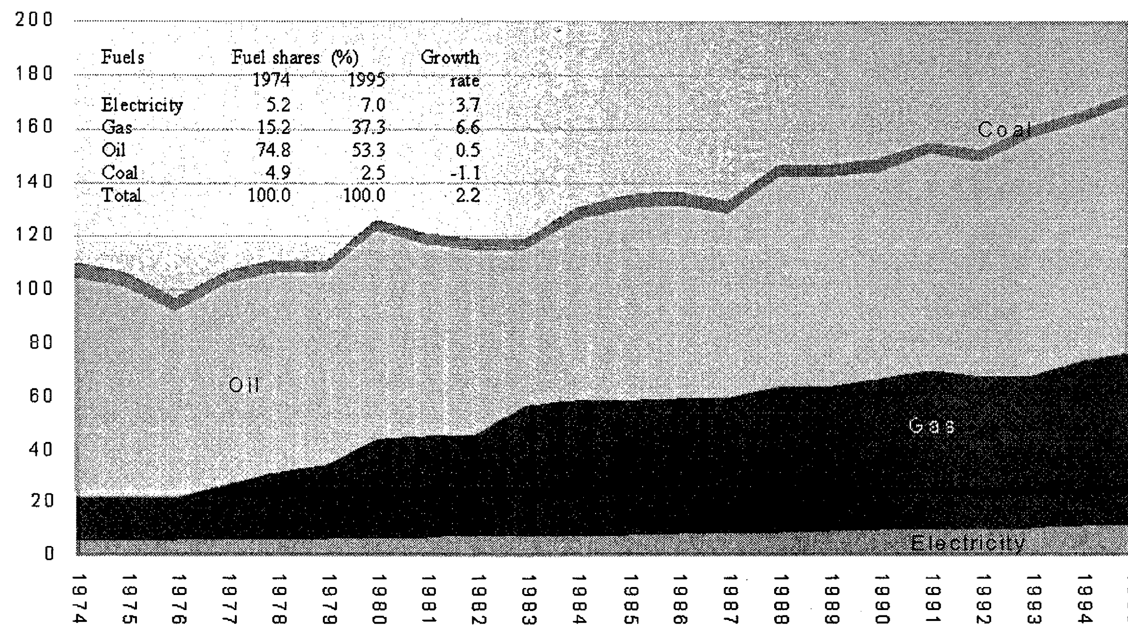
Notes: Theoretical values: 1 per cent = 2.66, 5 per cent = 2.0, 10 per cent = 1.67. The significance of the elasticities is not specified, mainly to leave the table simple.
Source: Author's estimations.

Given the strong substitutability between electricity and oil and a fairly high own-price elasticity of oil demand, it is possible that electricity consumption in the basic non-ferrous metals industry may have increased at the expense of oil. However, it is hard to associate the more than doubling of the gas share with the gas elasticities, both the own-price elasticity and the cross-price elasticities. Not only is the demand for the fuel nearly insensitive to own-price movements but also it tends to be a complement to oil and coal. The massive restructuring in the fuel mix is probably due to technical progress which has been electricity and gas consuming, but oil and coal saving.[6] An increase in the price of coal relative to that of the other three fuels is not likely to alter the fuel mix in favour of gas given the complementary relationship between the two fuels.

8.2.3 Basic chemicals

The basic chemicals industry stands third in the manufacturing sector with a total energy consumption of 110.3 PJ in 1974. Growing at an average rate of about 2.2 per cent a year, total energy use in the industry rose to 173.4 PJ in the 22-year period to 1995 (Figure 8.5). Electricity and gas consumption grew much faster – electricity by 3.7 per cent and gas by 6.6 per cent – while oil consumption grew significantly slower, at 0.5 per cent a year. Coal consumption, on the other hand, shrank at the rate of about 1 per cent a year to 4.3 PJ in 1995.

Figure 8.5 **Basic chemicals, energy consumption by fuel** (peta joules)



Source: Bush *et al.* 1999. *Australian Energy: market developments and projections to 2014-15*, Research Report No. 99.4, Australian Bureau of Agricultural and Resource Economics, Canberra.

Oil dominates the industry's energy mix, although its importance has declined from nearly three-quarters in 1974 to more than one-half in 1995. The significance of gas as a fuel source, on the other hand, increased by about 22 percentage points to 37.3 per cent in 1995, giving an impression that gas may have replaced oil in some of the production processes of the basic chemicals industry. The share of electricity, a relatively minor fuel source, increased to 7 per cent in 1995 from 5.2 per cent in 1974. In contrast, the coal share fell by about 50 per cent to 2.5 per cent over the 22-year period.

Gas demand is not only quite sensitive to own-price movements but also it is a significant substitute for oil and coal (Table 8.3). The cross-price elasticity of gas with respect to the oil price is quite large; it is nearly as high as the own-price elasticity of gas (in absolute terms). On the other hand, the demand for oil – the biggest energy source in the industry – is very much own-price inelastic and as well the cross-price sensitivities are very small, reflecting the near independence of the fuel source from various fuel prices. Coal consumption is quite responsive to own-price movements although the responsiveness has decreased over time. Also, coal is a substitute for gas but a complement to oil.

Table 8.3 **Basic chemicals, inter-fuel price elasticities for selected years**

Years	value	t-score	value	t-score	value	t-score	value	t-score
	Electricity							
	ε_{11}		ε_{12}		ε_{13}		ε_{14}	
1975	-0.344	23.42	0.053	2.19	0.277	11.03	0.014	8.64
1980	-0.072	3.03	0.018	0.45	0.050	1.23	0.004	1.66
1985	0.141	4.63	0.000	0.01	-0.141	2.71	0.000	0.14
1990	0.015	0.57	0.015	0.35	-0.031	0.67	0.000	0.09
1995	0.000	0.01	0.020	0.46	-0.018	0.41	-0.001	0.43
	Gas							
	ε_{21}		ε_{22}		ε_{23}		ε_{24}	
1975	0.073	2.19	-0.784	11.52	0.647	7.89	0.065	10.45
1980	0.016	0.45	-0.782	10.76	0.706	8.07	0.060	9.05
1985	0.000	0.01	-0.783	11.06	0.727	8.53	0.056	8.65
1990	0.012	0.35	-0.784	11.50	0.719	8.77	0.053	8.54
1995	0.015	0.46	-0.784	11.86	0.719	9.03	0.050	8.30
	Oil							
	ε_{31}		ε_{32}		ε_{33}		ε_{34}	
1975	0.050	11.03	0.086	7.89	-0.143	9.91	0.007	10.47
1980	0.005	1.23	0.080	8.07	-0.085	6.43	0.000	0.75
1985	-0.011	2.71	0.083	8.53	-0.069	5.33	-0.003	5.12
1990	-0.003	0.67	0.087	8.77	-0.080	6.07	-0.004	6.81
1995	-0.002	0.41	0.090	9.03	-0.082	6.24	-0.006	9.55
	Coal							
	ε_{41}		ε_{42}		ε_{43}		ε_{44}	
1975	0.114	8.64	0.378	10.45	0.302	10.47	-0.793	43.34
1980	0.042	1.66	0.627	9.05	-0.041	0.75	-0.628	17.87
1985	0.005	0.14	0.871	8.65	-0.411	5.12	-0.466	9.12
1990	0.004	0.09	1.013	8.54	-0.644	6.81	-0.373	6.21
1995	-0.027	0.43	1.432	8.30	-1.314	9.55	-0.091	1.04

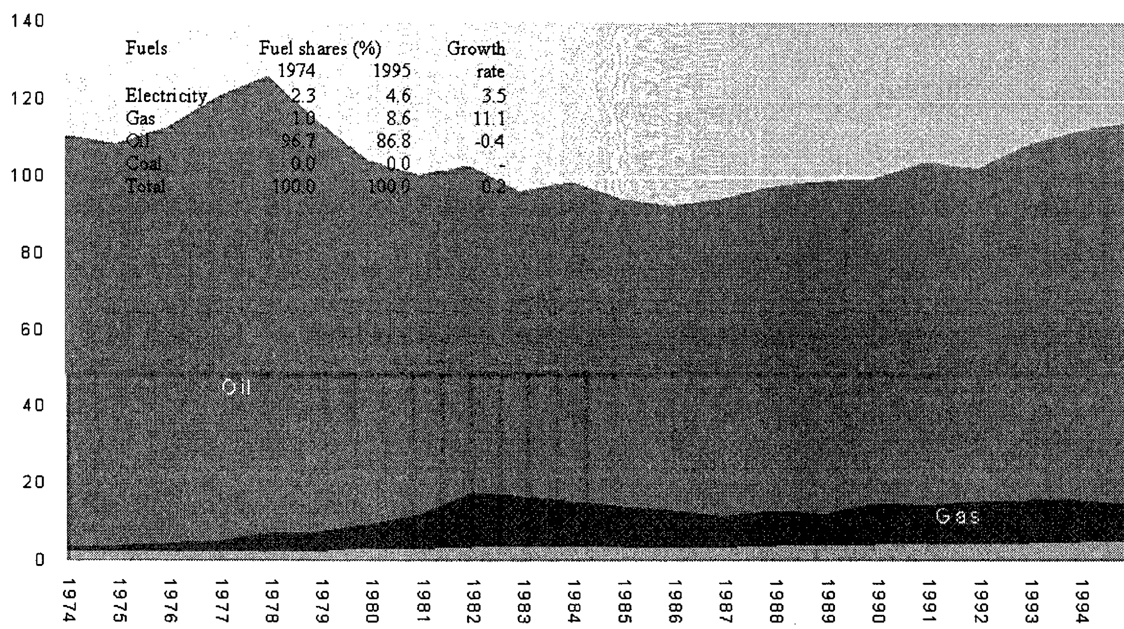
Notes: Theoretical values: 1 per cent = 2.66, 5 per cent = 2.0, 10 per cent = 1.67. The significance of the elasticities is not specified, mainly to leave the table simple.
Source: Author's estimations.

An increase in the prices of coal and oil relative to that of gas, is likely to enhance gas use and contract coal consumption, without noticeably reducing oil demand in the industry. Indeed, a sharp increase in gas consumption during the 22-year period under analysis may have been in part due to rapidly rising oil prices, as the two fuels are strong substitutes. The near insensitivity of oil demand to various fuel prices, especially to own-price, has probably been instrumental in keeping the fuel use roughly stagnant during this period, despite the massive oil price inflation.

8.2.4 Petroleum refining

Energy consumption in petroleum refining stood at 110.7 PJ in 1974, amounting to approximately 9.2 per cent of the manufacturing sector's gross energy use for the year.[7] During the 22-year period to 1995, electricity and gas use rose by a factor of two and nine respectively but oil – the dominant fuel source – shrank by 7 per cent, leading to a moderate expansion in total energy consumption in the industry to 114.2 PJ. Coal consumption in the industry is virtually zero (Figure 8.6).

Figure 8.6 **Petroleum refining, energy consumption by fuel** (peta joules)



Source: Bush *et al.* 1999. *Australian Energy: market developments and projections to 2014-15*, Research Report No. 99.4, Australian Bureau of Agricultural and Resource Economics, Canberra.

Oil dominance in the fuel mix has fallen from as high as 96.7 per cent in the early 1970s to about 86.8 per cent in the mid 1990s due to the high growth rate in electricity and gas use. The gas share increased by more than 7 percentage points to 8.6 per cent in 1995.

The demand for electricity and gas is quite responsive to own-prices, as well the two fuels are significant substitutes for oil (Table 8.4). This is especially true for gas, as both the own-price and the cross-price elasticity with respect to the oil price exceed unity (in absolute terms). The own-price elasticity of oil demand is, however, very low; less than

0.1 (in absolute terms). Therefore, an increase in the price of oil relative to that of gas caused by, say, a carbon tax is likely to increase gas consumption without significantly containing oil consumption in the industry.

Table 8.4 **Petroleum refining, inter-fuel price elasticities for selected years**

Years	value	t-score	value	t-score	value	t-score	value	t-score
				Electricity				
	ε_{11}		ε_{12}		ε_{13}		ε_{14}	
1975	-0.464	2.04	-0.025	0.13	0.488	6.10	..	..
1980	-0.346	1.19	-0.014	0.06	0.360	3.52	..	..
1985	-0.341	1.16	-0.013	0.05	0.354	3.42	..	..
1990	-0.419	1.66	-0.007	0.03	0.425	4.79	..	..
1995	-0.449	1.91	-0.002	0.01	0.451	5.45	..	..
				Gas				
	ε_{21}		ε_{22}		ε_{23}		ε_{24}	
1975	-0.171	0.13	-3.202	2.93	3.372	5.83	..	..
1980	-0.024	0.06	-1.671	4.82	1.695	9.25	..	..
1985	-0.020	0.05	-1.626	5.00	1.647	9.57	..	..
1990	-0.013	0.03	-1.634	4.96	1.647	9.46	..	..
1995	-0.004	0.01	-1.590	5.16	1.594	9.78	..	..
				Oil				
	ε_{31}		ε_{32}		ε_{33}		ε_{34}	
1975	0.034	6.10	0.034	5.83	-0.068	8.02	..	..
1980	0.020	3.52	0.054	9.25	-0.074	8.68	..	..
1985	0.019	3.42	0.056	9.57	-0.076	8.83	..	..
1990	0.027	4.79	0.056	9.46	-0.083	9.66	..	..
1995	0.031	5.45	0.058	9.78	-0.090	10.31	..	..

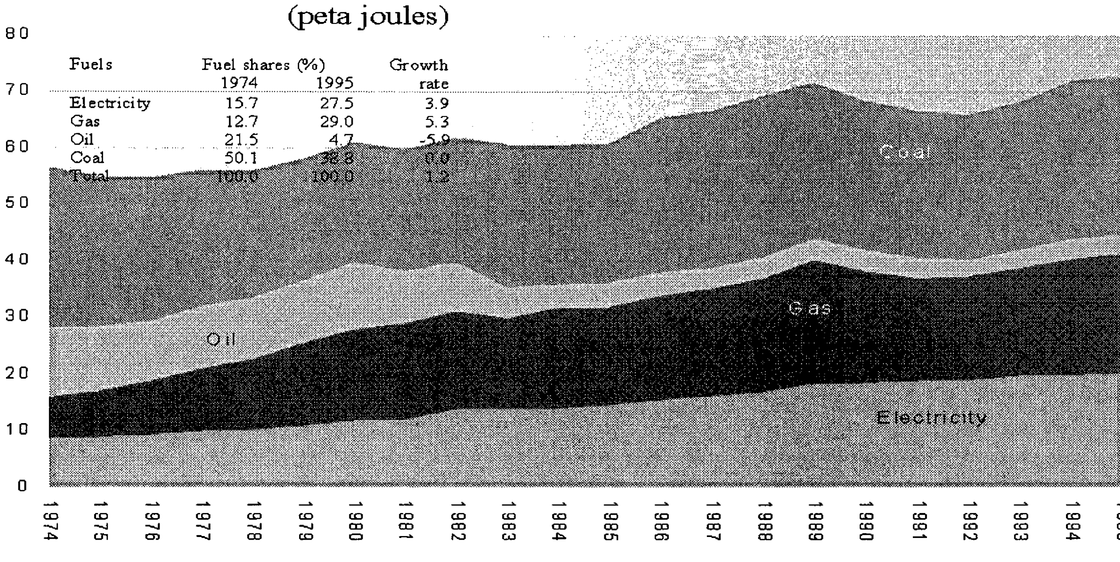
Notes: Theoretical values: 1 per cent = 2.66, 5 per cent = 2.0, 10 per cent = 1.67. The significance of the elasticities is not specified, mainly to leave the table simple.
Source: Author's estimations.

8.2.5 Wood, paper and printing

This is a relatively small industry on the energy consumption scale, accounting for around 4.7 per cent of the sector's gross energy consumption in 1974. Total energy consumption in this industry increased by 29 per cent to 72.8 PJ between 1974 and 1995 (Figure 8.7). While coal consumption remained more or less stable around the 28 PJ mark, oil consumption fell by 72 per cent and that of electricity and gas rose by factors of 2.3 and 3 over the period under consideration.

Because of massive restructuring in the industry, the coal share fell from more than one-half in the early 1970s to 38.8 per cent in the mid-1990s. In contrast, the combined shares of electricity and gas swelled by 28 percentage points to 56.6 per cent in 1995. Like most other industrial branches, the oil share shrank significantly; its share fell by about 17 percentage points to just 4.7 per cent in the industry over the 22-year period.

Figure 8.7 **Wood, paper and printing, energy consumption by fuel** (peta joules)



Source: Bush *et al.* 1999. *Australian Energy: market developments and projections to 2014-15*, Research Report No. 99.4, Australian Bureau of Agricultural and Resource Economics, Canberra.

Gas demand is the most (own) price responsive of all fuels, with roughly unit elasticity (Table 8.5). This is followed by oil with an elasticity range of -0.56 in 1975 to -0.27 in 1995. Coal price responsiveness is fairly similar, with a slightly lower range of -0.52 to -0.36. Conversely, electricity demand is the least elastic of all fuels with an elasticity of -0.11 in 1995. Interestingly, electricity demand is also not very sensitive to the prices of the other three fuels. Gas, in contrast, is found to be a significant substitute for the other three fuels. On the other hand, oil and coal tend to be complementary fuels. Given these price sensitivities, it seems that there exists a considerable potential to substitute away from coal and oil to gas in this industry.

Table 8.5 **Wood, paper and printing, inter-fuel price elasticities for selected years**

Years	value	t-score	value	t-score	value	t-score	value	t-score
	Electricity							
	ε_{11}		ε_{12}		ε_{13}		ε_{14}	
1975	-0.202	2.41	0.047	0.70	0.137	5.35	0.018	0.53
1980	-0.188	2.36	0.073	1.15	0.114	4.71	0.000	0.01
1985	-0.177	2.31	0.089	1.44	0.088	3.75	0.000	0.01
1990	-0.145	2.07	0.099	1.75	0.048	2.23	-0.002	0.05
1995	-0.106	1.65	0.102	1.97	0.010	0.50	-0.006	0.23
	Gas							
	ε_{21}		ε_{22}		ε_{23}		ε_{24}	
1975	0.204	0.70	-1.086	4.10	0.398	4.59	0.484	3.99
1980	0.283	1.15	-1.031	4.62	0.343	4.70	0.404	3.96
1985	0.325	1.44	-1.002	4.92	0.302	4.52	0.375	4.02
1990	0.384	1.75	-0.994	4.99	0.252	3.86	0.358	3.94
1995	0.440	1.97	-0.999	4.94	0.210	3.17	0.349	3.78

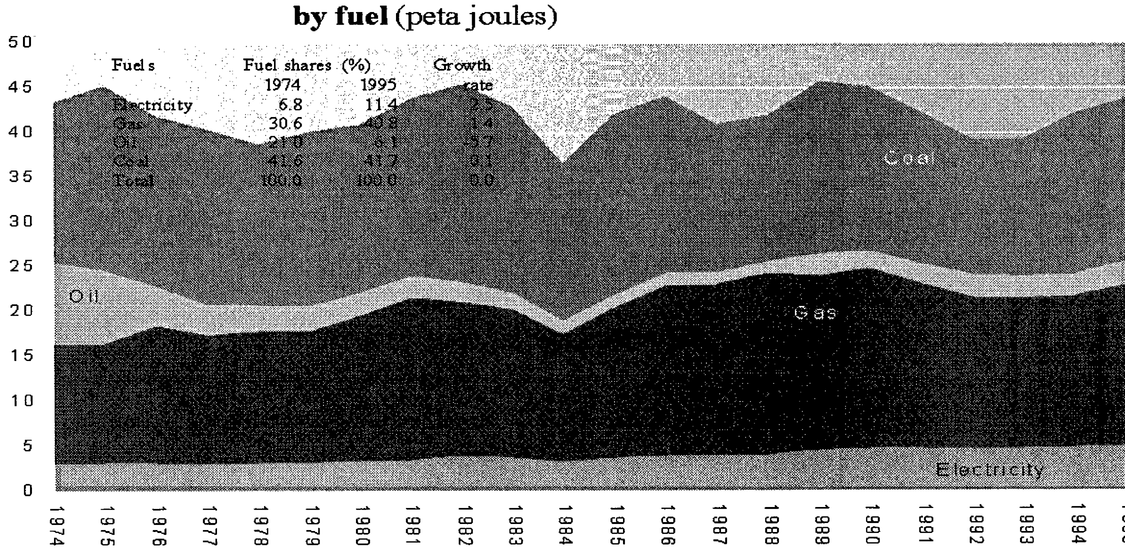
					Oil			
	ε_{31}		ε_{32}		ε_{33}		ε_{34}	
1975	0.330	5.35	0.221	4.59	-0.557	9.74	0.005	0.24
1980	0.331	4.71	0.258	4.70	-0.552	8.48	-0.037	1.55
1985	0.310	3.75	0.292	4.52	-0.536	7.00	-0.066	2.36
1990	0.259	2.23	0.349	3.86	-0.462	4.32	-0.145	3.69
1995	0.093	0.50	0.461	3.17	-0.249	1.44	-0.306	4.80
					Coal			
	ε_{41}		ε_{42}		ε_{43}		ε_{44}	
1975	0.072	0.53	0.440	3.99	0.008	0.24	-0.520	6.14
1980	-0.001	0.01	0.533	3.96	-0.065	1.55	-0.467	4.51
1985	-0.001	0.01	0.560	4.02	-0.103	2.36	-0.456	4.26
1990	-0.010	0.05	0.607	3.94	-0.178	3.69	-0.419	3.53
1995	-0.050	0.23	0.674	3.78	-0.268	4.80	-0.356	2.60

Notes: Theoretical values: 1 per cent = 2.66, 5 per cent = 2.0, 10 per cent = 1.67. The significance of the elasticities is not specified, mainly to leave the table simple.
Source: Author's estimations.

8.2.6 Cement, lime, plaster and concrete

The cement, lime plaster and concrete industry – a relatively minor energy-using industry with a near stagnant fuel use around the 40 PJ mark – depends mainly on gas and coal (Figure 8.8). The combined shares of the two fuels increased from 72.1 per cent in 1975 to 82.5 per cent in 1995 due to a 10-percentage point increase in the gas share. As in most other industries, the oil share fell substantially over the years, due to an average contraction rate of 5.7 per cent a year in the consumption of the fuel. The share fell from about one-fifth in 1975 to almost 3 per cent in 1987 but rose steadily to 6.1 per cent in 1995.

Figure 8.8 **Cement, lime, plaster and concrete, energy consumption by fuel** (peta joules)



Source: Bush *et al.* 1999. *Australian Energy: market developments and projections to 2014-15*, Research Report No. 99.4, Australian Bureau of Agricultural and Resource Economics, Canberra.

The oil demand elasticity exceeds unity (in absolute terms), whereas that of the other three fuels is less than unity; however, the degree of price responsiveness is considerable in these three fuels (Table 8.6). In the case of coal, for instance, the elasticity ranges between -0.37 in 1975, and -0.15 in 1995. The coal demand elasticity in 1995 is markedly lower and insignificant, probably due to the concavity restrictions. The electricity and gas elasticities have been stable around -0.27 and -0.31 respectively. Significant substitution opportunities are found between gas and oil and between oil and coal. However, the two main fuel sources – gas and coal – tend to be complementary, especially during the early 1990s. Therefore, a switch from coal to gas is not likely in the cement industry.

Table 8.6 **Cement, lime, plaster and concrete, inter-fuel price elasticities for selected years**

Years	value	t-score	value	t-score	value	t-score	value	t-score
	Electricity							
	ε_{11}		ε_{12}		ε_{13}		ε_{14}	
1975	-0.263	1.86	0.039	0.47	0.120	3.99	0.105	1.17
1980	-0.272	2.06	0.057	0.73	0.088	3.14	0.127	1.52
1985	-0.274	2.11	0.080	1.05	0.097	3.52	0.097	1.18
1990	-0.279	2.38	0.089	1.28	0.116	4.69	0.074	0.99
1995	-0.277	2.56	0.105	1.63	0.127	5.54	0.045	0.66
	Gas							
	ε_{21}		ε_{22}		ε_{23}		ε_{24}	
1975	0.035	0.47	-0.311	3.99	0.323	4.89	-0.047	0.94
1980	0.054	0.73	-0.311	3.97	0.288	4.34	-0.031	0.63
1985	0.074	1.05	-0.312	4.20	0.288	4.57	-0.050	1.07
1990	0.095	1.28	-0.311	3.98	0.310	4.68	-0.094	1.89
1995	0.122	1.63	-0.311	3.96	0.318	4.77	-0.129	2.59
	Oil							
	ε_{31}		ε_{32}		ε_{33}		ε_{34}	
1975	0.195	3.99	0.594	4.89	-1.109	6.93	0.320	4.46
1980	0.191	3.14	0.657	4.34	-1.216	6.09	0.367	4.11
1985	0.203	3.52	0.659	4.57	-1.191	6.27	0.328	3.86
1990	0.247	4.69	0.615	4.68	-1.146	6.62	0.284	3.66
1995	0.281	5.54	0.601	4.77	-1.126	6.78	0.245	3.28
	Coal							
	ε_{41}		ε_{42}		ε_{43}		ε_{44}	
1975	0.158	1.17	-0.079	0.94	0.297	4.46	-0.375	5.19
1980	0.189	1.52	-0.049	0.63	0.252	4.11	-0.392	5.88
1985	0.173	1.18	-0.098	1.07	0.278	3.86	-0.354	4.51
1990	0.176	0.99	-0.209	1.89	0.319	3.66	-0.286	3.02
1995	0.152	0.66	-0.370	2.59	0.371	3.28	-0.153	1.25

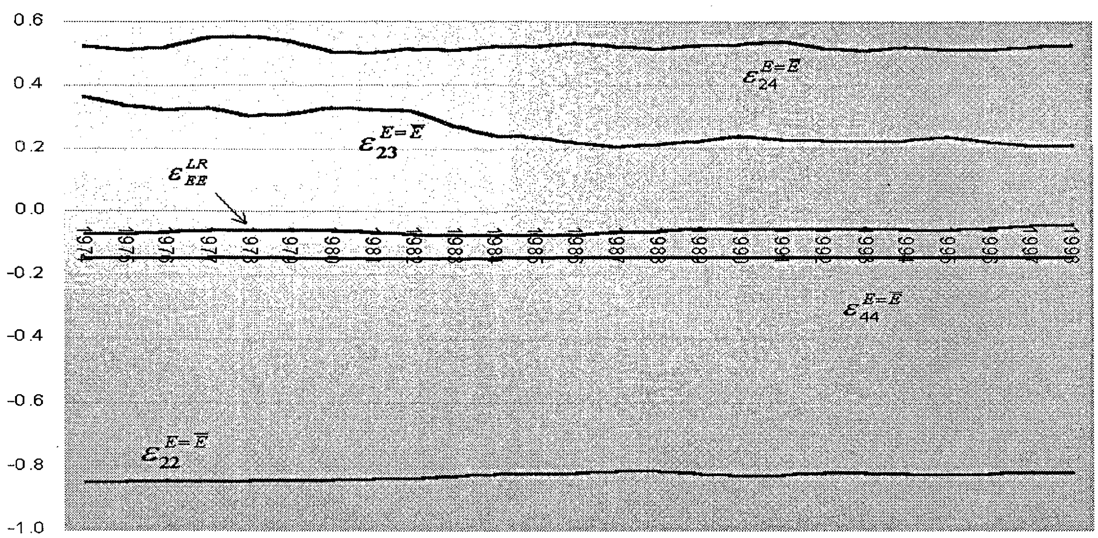
Notes: Theoretical values: 1 per cent = 2.66, 5 per cent = 2.0, 10 per cent = 1.67. The significance of the elasticities is not specified, mainly to leave the table simple.
Source: Author's estimations.

8.3 Electricity, gas and water

The electricity, gas and water (E-G-W) sector has been the largest energy-consuming sector since 1983. Its share in gross national energy consumption grew from about one-fourth in 1974 to more than 35 per cent in 1998 on the back of an impressive expansion of the power industry. Historically, E-G-W has depended heavily on coal, as the coal share was about 80 per cent of gross energy consumed by the sector during the early 1970s. The sector's reliance on the fuel has increased, particularly during the late 1990s; in 1998, the coal share was estimated at about 85 per cent.

Given the sheer size of energy use in the sector and more importantly its heavy reliance on coal, the elasticities characterising inter-fuel substitutions are of paramount interest. The long-run own-price elasticity of the aggregate energy input along with some inter-fuel elasticities are shown in Figure 8.9. Looking at the own-price elasticity of aggregate energy, it is quite clear that energy demand is highly price inelastic. A 10 per cent increase in energy price is likely to reduce the demand for energy by less than 0.4 per cent once the capital stock has fully adjusted to a new steady-state level.

Figure 8.9 **E-G-W, selected energy demand elasticities**



Source: Author's estimations.

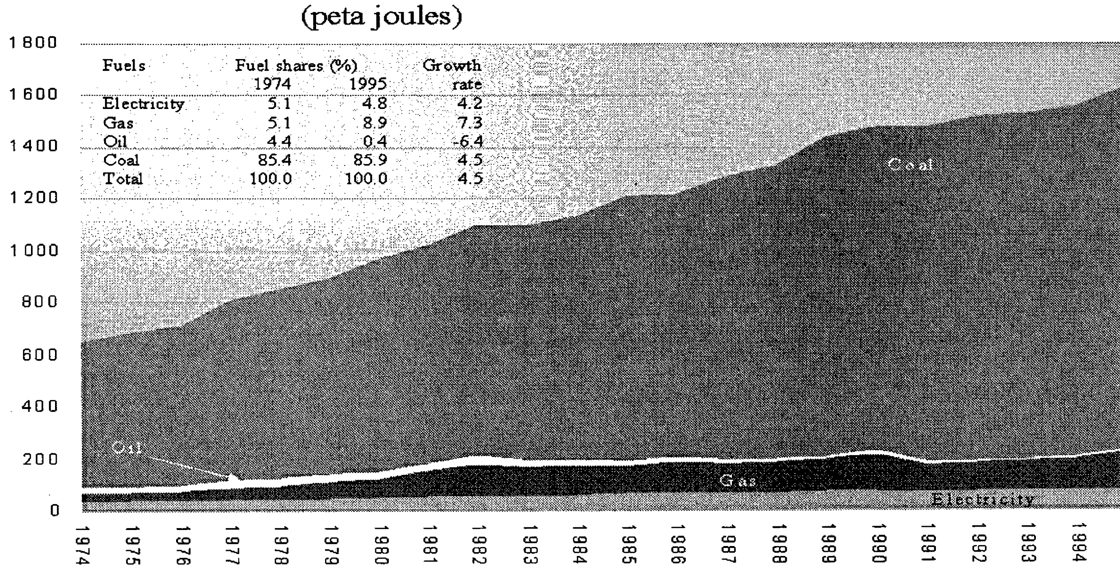
Although total energy demand in the sector is nearly independent of energy price movements, the inter-fuel price elasticities show some sign of flexibility. Coal demand, for instance, is expected to shrink by about 1.4 per cent in response to a 10 per cent rise in the fuel price if aggregate energy use in the sector is held constant. Gas demand is much more responsive with an own-price elasticity of -0.82 in 1995. Thus a 10 per cent reduction in gas price may enhance its use by more than 8 per cent by way of reducing the use of other fuels, including coal. Gas is also a significant substitute for oil and coal, especially coal, with inter-fuel price elasticities of 0.21 and 0.53 respectively. The corresponding long-run elasticities (E variable but output, Q, constant, not reported in the figure) are only slightly lower due to the near independence of aggregate energy demand from the energy price. Thus, there exists some potential for switching from coal to gas in the sector (E-G-W) which employed about 70 per cent of total coal use in the economy in 1998.

In order to investigate this potential further, the inter-fuel elasticities relating to the public and private electricity generation sub-sectors – which dominate E-G-W with a combined share of 98.7 per cent in 1995 – are analysed in the following two subsections. Before moving on to analysing the substitution opportunities, the energy structures in the two sub-sectors are briefly discussed.

8.3.1 Public electricity generation

The public electricity generation sector overwhelmingly dominated electricity, gas and water with energy use of 650.7 PJ in 1974, accounting for more than 88 per cent of the sector's total energy use in that year. Over the 22-year period to 1995, it increased 4.5-fold to 1634.6 PJ. As a result, the sub-sector's share in E-G-W's total energy consumption rose to approximately 95 per cent. The coal share in public electricity generation has been almost stable at around 85 per cent; the gas share increased to nearly 9 per cent in 1995 from 5.1 per cent in 1974. Meanwhile, the oil share fell by 4 percentage point to just 0.4 per cent (see Figure 8.10).

Figure 8.10 **Public electricity generation, energy consumption by fuel** (peta joules)



Source: Bush *et al.* 1999. *Australian Energy: market developments and projections to 2014-15*, Research Report No. 99.4, Australian Bureau of Agricultural and Resource Economics, Canberra.

The price sensitivities for public electricity generation are typically small in relation to their counterparts characterising the E-G-W sector and not significant at the 5 per cent level in most cases (Table 8.7). While the own-price elasticity of coal is only slightly lower (in absolute terms), the gas elasticity is considerably smaller with a value of -0.63 in 1995. Similarly, the cross-price elasticities of gas demand with respect to oil and coal are also small. In contrast, the electricity elasticity is relatively large. While the above three elasticities have been fairly stable, the oil elasticity has fallen sharply from -0.65 in 1975 to -0.06 in 1995. On average, it is clear that flexibility in the use of the four fuels is relatively less in public electricity generation than in the E-G-W sector as a whole.

Table 8.7 **Public electricity generation, inter-fuel price elasticities for selected years**

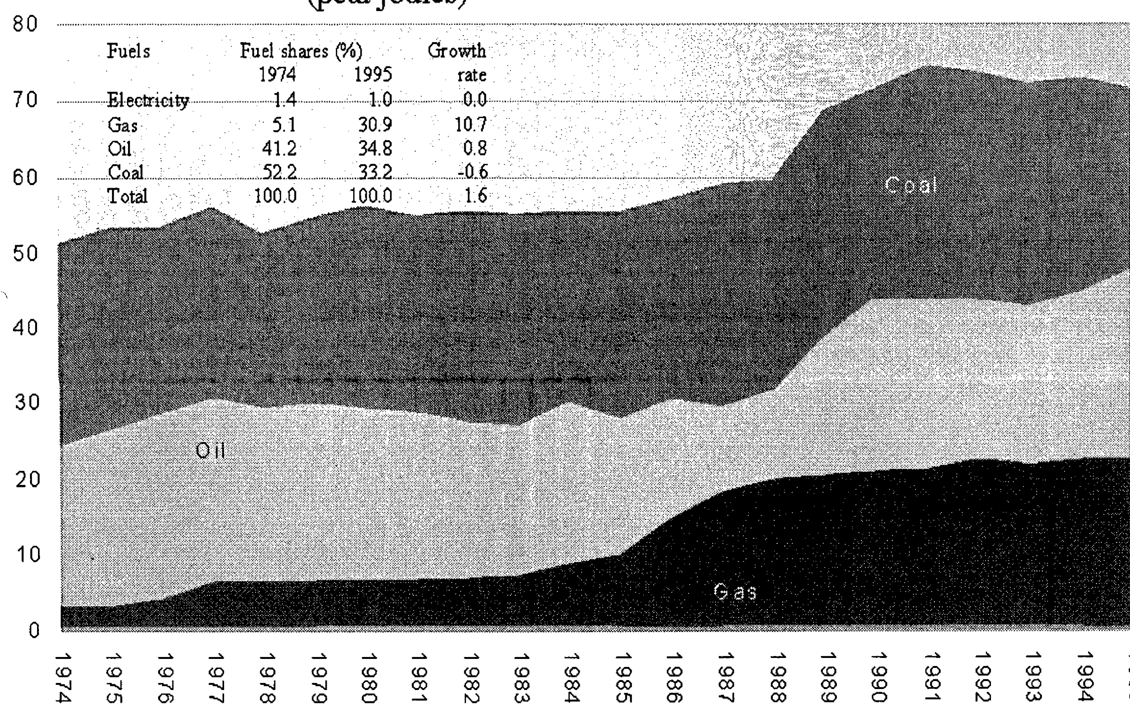
Years	value	t-score	value	t-score	value	t-score	value	t-score
				Electricity				
	ε_{11}		ε_{12}		ε_{13}		ε_{14}	
1975	-0.166	1.86	0.027	0.38	0.076	2.91	0.062	1.06
1980	-0.157	1.67	0.033	0.44	0.065	2.33	0.060	0.96
1985	-0.143	1.43	0.047	0.58	0.047	1.58	0.050	0.76
1990	-0.154	1.61	0.062	0.81	0.026	0.91	0.066	1.05
1995	-0.161	1.75	0.079	1.07	0.010	0.36	0.073	1.20
				Gas				
	ε_{21}		ε_{22}		ε_{23}		ε_{24}	
1975	0.106	0.38	-0.551	1.33	0.151	0.83	0.293	0.78
1980	0.111	0.44	-0.575	1.53	0.135	0.82	0.330	0.96
1985	0.124	0.58	-0.608	1.91	0.109	0.79	0.375	1.29
1990	0.155	0.81	-0.623	2.17	0.083	0.66	0.384	1.47
1995	0.185	1.07	-0.634	2.46	0.062	0.55	0.387	1.65
				Oil				
	ε_{31}		ε_{32}		ε_{33}		ε_{34}	
1975	0.283	2.91	0.144	0.83	-0.653	11.13	0.227	1.46
1980	0.258	2.33	0.160	0.82	-0.630	9.44	0.211	1.20
1985	0.221	1.58	0.195	0.79	-0.570	6.78	0.155	0.70
1990	0.192	0.91	0.249	0.66	-0.403	3.15	-0.038	0.11
1995	0.124	0.36	0.342	0.55	-0.062	0.29	-0.405	0.73
				Coal				
	ε_{41}		ε_{42}		ε_{43}		ε_{44}	
1975	0.044	1.06	0.054	0.78	0.043	1.46	-0.141	1.83
1980	0.039	0.96	0.064	0.96	0.034	1.20	-0.137	1.84
1985	0.029	0.76	0.083	1.29	0.019	0.70	-0.131	1.83
1990	0.041	1.05	0.095	1.47	-0.003	0.11	-0.132	1.83
1995	0.048	1.20	0.108	1.65	-0.021	0.73	-0.136	1.84

Notes: Theoretical values: 1 per cent = 2.66, 5 per cent = 2.0, 10 per cent = 1.67. The significance of the elasticities is not specified, mainly to leave the table simple.
Source: Author's estimations.

8.3.2 Private electricity generation

Private electricity generation is tiny in relation to its public sector counterpart. Moreover, its fuel structure is markedly different. With the public electricity generation sector's share of energy use in the E-G-W sector rising, the share of energy use of the private sector fell from 7 per cent in 1974 to a little more than 4 per cent in 1995. In 1974, coal's share in the private sector stood at 52.2 per cent followed by oil and gas with shares of 41.2 per cent and 5.1 per cent, respectively (Figure 8.11). In 1995, each of the three fuel sources contributed roughly one-third towards total energy consumption, implying almost equal significance of the fuels in private electricity generation.

Figure 8.11 **Private electricity generation, energy consumption by fuel** (peta joules)



Source: Bush *et al.* 1999. ***Australian Energy: market developments and projections to 2014-15***, Research Report No. 99.4, Australian Bureau of Agricultural and Resource Economics, Canberra.

Looking at the inter-fuel price elasticities presented in Table 8.8, it is obvious that managers in private power plants have employed gas and coal in a much more flexible manner. The own-price elasticity of coal has ranged between -0.69 and -0.72. The corresponding gas price elasticity shows an even greater degree of sensitivity; the elasticity has changed from nearly unity in the mid-1970s to -0.78 in 1995. Similarly, the electricity price elasticity has also been high. However, the demand for oil is very price inelastic compared to oil demand in the public sector which was quite sensitive up until the 1990s.

Table 8.8 **Private electricity generation, inter-fuel price elasticities for selected years**

Years	value	t-score	value	t-score	value	t-score	value	t-score
				Electricity				
	ε_{11}		ε_{12}		ε_{13}		ε_{14}	
1975	-0.662	8.87	0.434	3.92	0.379	4.86	-0.151	1.63
1980	-0.561	5.13	0.604	3.72	0.348	3.05	-0.391	2.87
1985	-0.485	3.64	0.782	3.96	0.218	1.56	-0.515	3.10
1990	-0.418	2.73	0.931	4.09	0.123	0.77	-0.635	3.32
1995	-0.328	1.82	1.105	4.14	0.013	0.07	-0.790	3.52
				Gas				
	ε_{21}		ε_{22}		ε_{23}		ε_{24}	
1975	0.440	3.92	-0.962	2.53	-0.759	1.71	1.281	5.02
1980	0.417	3.72	-0.962	2.53	-0.665	1.50	1.210	4.74
1985	0.236	3.96	-0.885	4.37	-0.054	0.23	0.703	5.18
1990	0.176	4.09	-0.829	5.68	0.130	0.76	0.522	5.33
1995	0.144	4.14	-0.783	6.64	0.220	1.60	0.419	5.30
				Oil				
	ε_{31}		ε_{32}		ε_{33}		ε_{34}	
1975	0.042	4.86	-0.083	1.71	-0.065	0.90	0.106	4.43
1980	0.023	3.05	-0.064	1.50	-0.008	0.13	0.049	2.34
1985	0.013	1.56	-0.010	0.23	-0.037	0.55	0.035	1.57
1990	0.006	0.77	0.036	0.76	-0.051	0.74	0.009	0.39
1995	0.001	0.07	0.076	1.60	-0.059	0.84	-0.018	0.75
				Coal				
	ε_{41}		ε_{42}		ε_{43}		ε_{44}	
1975	-0.051	1.63	0.424	5.02	0.320	4.43	-0.694	8.76
1980	-0.134	2.87	0.600	4.74	0.253	2.34	-0.718	6.07
1985	-0.153	3.10	0.691	5.18	0.180	1.57	-0.718	5.74
1990	-0.197	3.32	0.854	5.33	0.054	0.39	-0.711	4.74
1995	-0.266	3.52	1.083	5.30	-0.131	0.75	-0.686	3.58

Notes: Theoretical values: 1 per cent = 2.66, 5 per cent = 2.0, 10 per cent = 1.67. The significance of the elasticities is not specified, mainly to leave the table simple.
Source: Author's estimations.

Coal and gas are strong substitutes in private electricity generation. This can be seen clearly by comparing the substitution elasticity between the two fuels (σ_{24}) instead of comparing the corresponding cross-price elasticities across the two sub-sectors. The substitution elasticity between the two fuels in private power plants has fluctuated between 6.16 (1975) and 4.86 (1995), whereas in the public sector plants the elasticity has assumed values between 0.31 and 0.56. Furthermore, in the public sector σ_{24} is largely insignificant while in the private sector it is significantly different from zero at the 99 per cent level of confidence. It is, however, worth noting that in the private sector the cross-price elasticity of gas demand with respect to the coal price has declined considerably – from 1.28 in 1974 to 0.42 in 1995.

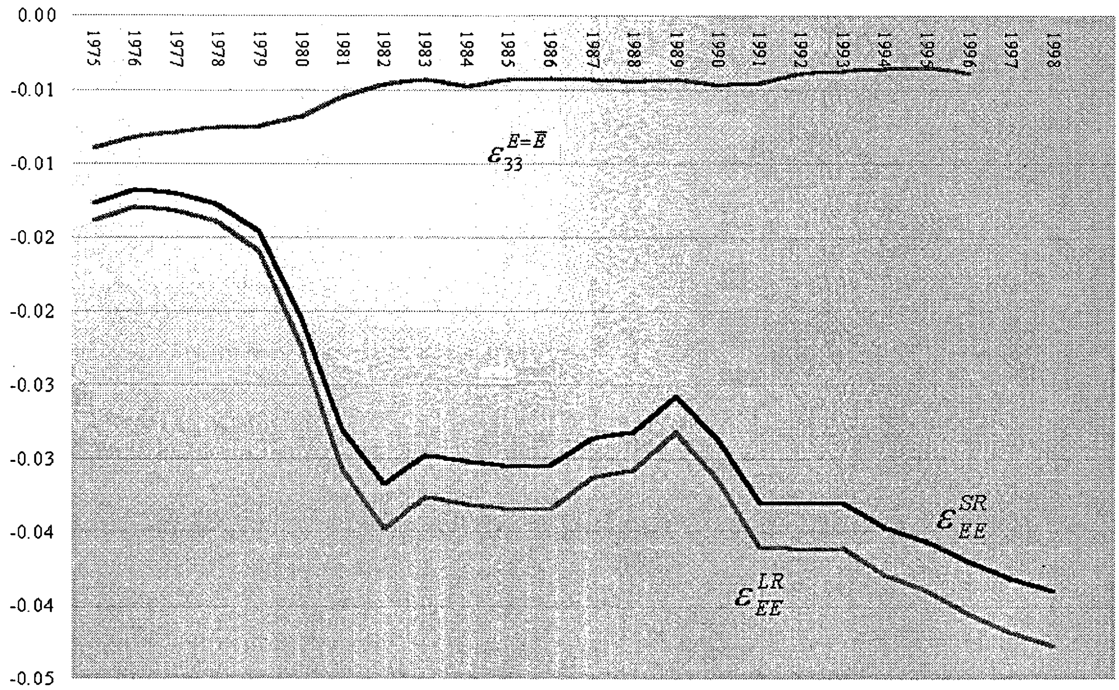
Low inter-fuel substitution opportunities in the public sector power plants reflect the Australian government's relatively greater emphasis on stability rather than on efficiency in power supply in the past. However, the reform process that began in the electricity and gas markets in the early 1990s, and the consequent emergence of a national electricity market, imply that historical data-based estimates of the inter-fuel substitutions underestimate the true potential in the changed environment. Because of the integrated market, brown coal found mainly in Victoria has become a good substitute for black coal found largely in Queensland. Likewise, gas can more easily be substituted for both black and brown coal as the electricity market integration has enhanced electricity mobility. Thus, a relative fuel price change, reflecting the carbon intensities of different fuels, is likely to change the fuel mix in power generation in favour of gas much more significantly than what is implied by the estimated elasticities for the public sector. Probably, therefore, the private sector elasticities better represent the fuel substitution opportunities in the entire power generation sector in the new situation.

8.4 Transport, storage and communication

Transport is the third largest energy consuming industry after E-G-W and manufacturing. Total energy use in the sector – sourced almost exclusively from petroleum products, oil – increased by about 80 per cent to 1210.7 PJ in the 25-year period to 1998, indicating an average growth rate of 2.4 per cent a year. During this period, the sector's share in gross national energy consumption remained nearly stable at around 22 per cent.

Given the overwhelming importance of oil as a fuel source and the limited substitution opportunities dictated by the transport technology, energy use behaviour in the sector is nearly fully characterised by the energy demand elasticity. The own-price elasticity of total energy demand, both short and long-run, based on the dynamic factor demands model estimated in the previous chapter is depicted in Figure 8.12. Also included in the figure is the own-price elasticity of oil ($\varepsilon_{33}^{E=\bar{E}}$) estimated from the application of the fuel choice model in Chapter 6.[8] Clearly, energy demand in this energy intensive sector is price insensitive. In the late 1970s, the short-run demand elasticity varied around -1.5 per cent. The second oil shock that hit the economy during 1979, increased the sensitivity temporarily to around -3 per cent. In more recent years, it has again increased slightly (in absolute terms). The long-run elasticity over the period tracks very closely the corresponding short-run estimate, indicating a small difference between the short and long-run energy demand responses. The own-price elasticity of oil (with E constant) is even lower; it has been less than -0.01 since the early 1980s, reflecting very little substitution potential in the transport industry.

Figure 8.12 **Transport, selected energy demand elasticities**



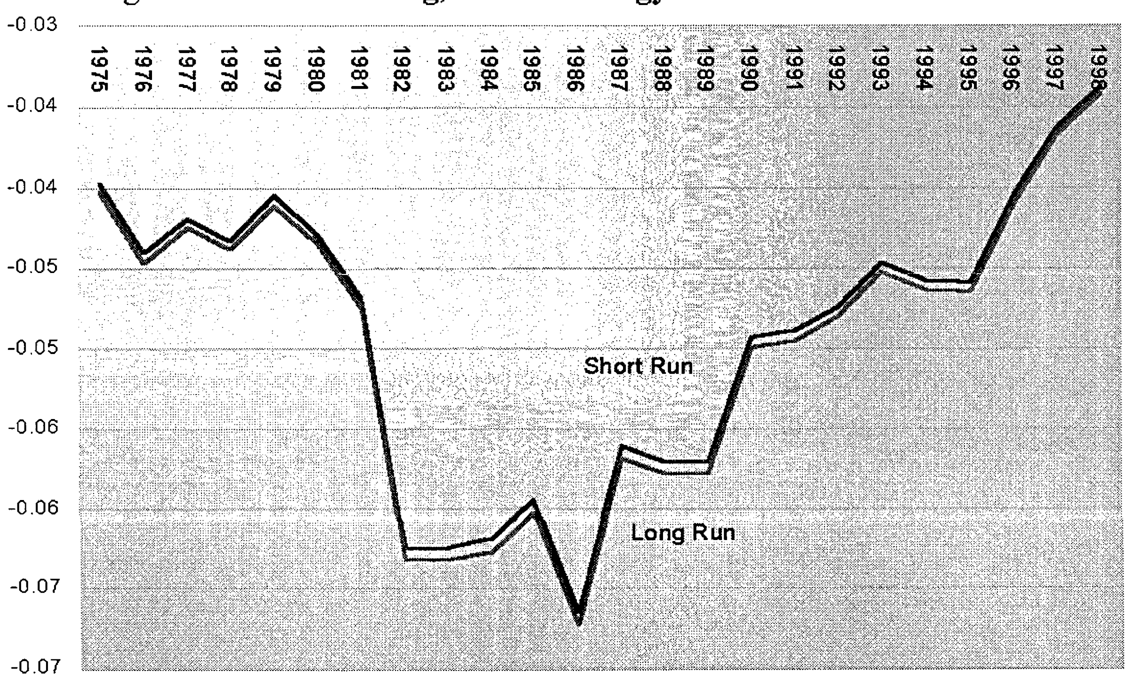
Source: Author's estimations.

8.5 Mining

Mining, although a relatively small energy consuming industry, experienced the fastest growth in fuel consumption across all industries during the 25-year period to 1998. During this period, total energy consumption grew at an average rate of 5 per cent a year to 278.2 PJ, a 3.3-fold increase. As opposed to the transport sector, the energy portfolio of the mining industry is fairly diverse, although in more recent years its dependence on coal has diminished remarkably from over 30 per cent to less than 10 per cent. Coal consumption declined at 0.8 per cent a year, leading to a 17 per cent reduction in the use of the fuel in mining. Gas consumption, in contrast, experienced an 11-fold increase, making it the single largest fuel source in 1998 from a relatively minor component in the early 1970s. Electricity and oil could not maintain their shares despite growing at 4.8 per cent and 3.1 per cent respectively, due largely to very high growth in gas use by the sector.

Energy demand in the sector is highly (own) price inelastic as is obvious from the short and long-run elasticities plotted in Figure 8.13. A 10 per cent increase in the price of energy is expected to reduce energy demand by less than 0.4 per cent once capital stock has fully adjusted to its new steady-state level. The oil crisis of the late 1970s increased the price sensitivity of energy demand slightly during the early 1980s. It is worth noting that the deviation between the short and the long-run elasticities is very small. As noted in the previous chapter, the difference between the two elasticities of a variable factor input such as energy is a product of two elasticities: the elasticity of K^* (the steady-state capital stock) with respect to energy price and the elasticity of E with respect to quantity K^*. In mining, the latter elasticity is nearly zero, leading to very similar short and long-run energy responses.

Figure 8.13 **Mining, selected energy demand elasticities**



Source: Author's estimations.

What about the inter-fuel substitution opportunities in the sector? In order to see this, the inter-fuel price elasticities (with E constant) based on the fuel choice model of Chapter 6 are presented in Table 8.9.[9] Some of the own-price elasticities are wrongly signed; the electricity elasticity is positive in 1985 and that of gas is positive in 1975 and 1980. However, these are not significant at the 5 per cent level. The own and cross-price elasticities of coal demand are fairly high and mostly significant, indicating the presence of substitution possibilities with other energy sources. However, the sensitivities for 1995 are relatively very small, probably because of the curvature restrictions. The two main fuels in the sector – gas and oil – are considerably own-price sensitive; the gas elasticity has increased from -0.17 in 1990 to -0.22 in 1995, whereas that of oil has been more or less stable around -0.16. The two fuel sources are significant substitutes during the 1990s; in particular, the cross-price elasticity of gas demand with respect to the oil price is nearly as large as the own-price elasticity of gas. Electricity demand is the least elastic of all fuels in terms of the own-price responsiveness. It tends to be a substitute for oil and coal, but complementary to gas. Given the accuracy of these parameters, a carbon tax is likely to reduce the GHG emissions in the sector somewhat not by reducing total energy use in the sector but by changing the fuel mix in favour of less carbon-intensive fuels.

Table 8.9 **Mining, inter-fuel price elasticities for selected years**

Years	value	t-score	value	t-score	value	t-score	value	t-score
				Electricity				
	ε_{11}		ε_{12}		ε_{13}		ε_{14}	
1975	-0.030	2.82	-0.074	2.69	0.054	1.58	0.050	19.16
1980	-0.023	1.94	-0.105	3.33	0.096	2.46	0.032	10.86
1985	0.006	0.46	-0.095	2.58	0.066	1.46	0.022	6.31
1990	-0.009	0.67	-0.042	1.21	0.037	0.86	0.014	4.27
1995	-0.002	0.14	-0.017	0.47	0.017	0.39	0.001	0.40
				Gas				
	ε_{21}		ε_{22}		ε_{23}		ε_{24}	
1975	-0.291	2.69	0.155	1.57	0.070	0.71	0.066	3.49
1980	-0.365	3.33	0.167	1.66	0.148	1.48	0.050	2.63
1985	-0.203	2.58	-0.079	1.10	0.242	3.35	0.040	2.95
1990	-0.078	1.21	-0.173	2.91	0.221	3.70	0.031	2.72
1995	-0.026	0.47	-0.224	4.37	0.232	4.51	0.018	1.86
				Oil				
	ε_{31}		ε_{32}		ε_{33}		ε_{34}	
1975	0.084	1.58	0.028	0.71	-0.140	1.72	0.029	3.74
1980	0.104	2.46	0.046	1.48	-0.169	2.61	0.019	3.18
1985	0.058	1.46	0.099	3.35	-0.170	2.76	0.012	2.16
1990	0.039	0.86	0.125	3.70	-0.164	2.34	0.000	0.01
1995	0.018	0.39	0.156	4.51	-0.161	2.25	-0.013	1.89
				Coal				
	ε_{41}		ε_{42}		ε_{43}		ε_{44}	
1975	0.408	19.16	0.137	3.49	0.150	3.74	-0.696	35.85
1980	0.313	10.86	0.140	2.63	0.173	3.18	-0.626	23.85
1985	0.223	6.31	0.192	2.95	0.144	2.16	-0.559	17.36
1990	0.200	4.27	0.235	2.72	0.001	0.01	-0.437	10.24
1995	0.034	0.40	0.289	1.86	-0.299	1.89	-0.024	0.31

Notes: Theoretical values: 1 per cent = 2.66, 5 per cent = 2.0, 10 per cent = 1.67. The significance of the elasticities is not specified, mainly to leave the table simple.
Source: Author's estimations.

8.6 Residential

Total energy consumption in the residential sector increased from 231.3 PJ in 1974 to 384.6 PJ in 1998, growing at an average rate of 2.1 per cent per annum. Because of a below-average growth rate, the sector's share in gross national energy consumption fell slightly from 7.5 per cent to 6.8 per cent during this period. In 1974, coal accounted for nearly 36 per cent of total energy consumption, followed by electricity (30.7 per cent), oil (19.8 per cent), and gas with a share of 13.5 per cent.[10] While coal consumption stayed nearly stable during this period of 25 years, electricity and gas use increased by factors of 2.4 and 3.5 respectively. In contrast, the oil use in 1998 fell to about one-third of the 1974-level. As a result, the electricity share increased to 43.5 per cent, and that of gas rose to 31.1 per cent. On the other hand, the coal and oil shares fell by 14.1 and 15.8 percentage points, respectively.

In the econometric analysis of the sector's energy demand, the use of all fuels other than electricity and gas were combined into one category – residual fuels – due to the non-availability of data. Four different estimates of the elasticities, estimated in Chapters 3 and 4, are presented in Table 8.10. A cursory look at the table reveals that energy demand in this sector is considerably more price responsive compared to the non-residential sector. In three cases, the own-price elasticity of electricity is greater than 0.6 (in absolute terms). The residual fuel demand tends to be own-price elastic. Similarly the gas elasticity shows significant flexibility in most cases.

As far as inter-fuel relationships are concerned, the VECM and the AREM, especially the VECM, find significant complementarity between electricity and gas – the two main fuels in the sector. The two cross-price elasticities are positive but insignificant in the top part of the table – the PANEL model. According to the DOLS, however, electricity and gas are strong substitutes. Electricity-other fuels and gas-other fuels tend to be substitutes in most cases.

The PANEL estimates are likely to better reflect more recent consumer energy demand behaviour, due mainly to two reasons: first, the data set used to estimate this set of estimates is more recent, covering the period from the third quarter 1984 to the second quarter 1998. The other three studies, on the other hand, employed data from 1970 to 1998. Second, the former estimates employ a panel data on five states whereas the other three estimates utilise the national-level data.

In the PANEL model, as mentioned above, the two cross-price elasticities between electricity and gas are insignificant, although positive. Also, the demand for electricity is relatively less elastic and the gas elasticity is not significant even at the 10 per cent level of significance. Growth in energy consumption in the sector is not likely to moderate because of the relatively moderate price sensitivities but rather higher income elasticities.

Table 8.10 **Residential sector: Marshallian demand elasticities**

Quantity	Price			Income
	Electricity	Gas	Residual fuels	
		I- PANEL		
Electricity	-0.353*	0.106	-0.031*	0.688*
Gas	0.683	-1.031	0.652*	2.354*
Residual fuels	-0.323	0.980*	-0.409*	1.170*
		II- Dynamic OLS (DOLS)		
Electricity	-0.951*	0.205**	0.377*	0.523*
Gas	0.870*	-0.702*	-0.186*	1.882*
Residual fuels	0.987*	1.295*	-1.168*	0.538*
		III- Vector error correction model (VECM)		
Electricity	-0.665*	-0.201*	0.203*	0.734*
Gas	-0.988*	-0.404	0.575**	1.133*
Residual fuels	1.416*	0.823**	-2.047*	0.505*
		IV- Autoregressive error model (AREM)		
Electricity	-0.677*	-0.082**	-0.047	0.805*
Gas	-0.256	-0.508*	0.126***	0.639**
Residual fuels	-1.103*	-0.111	-0.919*	2.133*

Notes: 1. PANEL estimates correspond to the application of the static Almost Ideal (AI) demand system in Chapter 3 to a panel data set. The VECM and AREM are also taken from Chapter 3, whereas the DOLS elasticities are reproduced from Chapter 4. 2. *- Significant at the 1 per cent level, ** significant at the 5 per cent level, *** significant at the 10 per cent level.

Source: Author's estimations.

8.7 Summary

The main aim in this chapter was to further investigate the energy demand structure estimated in different chapters of the thesis with a view to identifying the energy conservation potential, including inter-fuel substitution possibilities in different industries/sectors. In this respect, major energy consuming sectors namely manufacturing, electricity, gas and water, transport, storage and communication, mining and residential – with combined shares of total energy consumption of more than 94 per cent in 1998 – were chosen. Within manufacturing, attention focussed on six major energy using industries: iron and steel, basic non-ferrous metals, petroleum refining, basic chemicals, wood, paper and printing, and cement, lime, plaster and concrete. Similarly, in the electricity, gas and water sector, private and public electricity generation sub-sectors were further investigated to pinpoint such opportunities.

To this end, a two-step procedure, where applicable, was adopted. At the first stage, the energy conservation potential was explored at the sector level – for instance, manufacturing, electricity, gas and water – by employing the energy demand structure estimated using dynamic factor demands model in Chapter 7. At the second stage, the sub-sector level estimates of fuel structure were brought into the discussion. This detailed treatment helped not only pin down the inter-fuel opportunities but also played a crucial role in determining whether the sector level estimates of inter-fuel substitutions were not distorted because of aggregation across a heterogeneous set of industries. The results are summarised below.

Manufacturing

- The aggregate analysis finds significant energy conservation potential in the manufacturing sector. The demand for energy in aggregate is considerably own-price sensitive; as well, the inter-fuel price elasticities are fairly high (in absolute terms). The cross-price elasticities of gas demand show significant opportunities for substitution from oil and coal to gas.
- The fuel choice analysis of iron and steel – the single largest energy-using industry in manufacturing with a share of about 29 per cent (87 per cent of which is coal) – finds very limited inter-fuel substitution potential, especially from coal to gas (the second largest fuel source in the industry).
- In basic non-ferrous metals – the second largest energy-using manufacturing industry with a share of more than 20 per cent – the own-price elasticities show considerable flexibility. However, gas-oil and gas-coal tend to be in complementary relationships.
- Gas and oil are strong substitutes in the basic chemicals industry, which meets more than 90 per cent of its energy requirements from the two fuels.
- In petroleum refining, there is little possibility of replacing oil – the main fuel source with a share of about 87 per cent in 1995 – with other fuels, as oil demand is nearly independent of its own-price movements.
- Strong inter-fuel substitution opportunities are found in the wood, paper and printing industry, especially from oil and coal to gas.
- In the cement, lime, plaster and concrete industry, gas and coal – the two main fuels, accounting for more than 80 per cent of total fuel use in the industry – tend to be complements.

The aggregate analysis probably exaggerates the underlying inter-fuel substitution potential in the sector because, according to the fuel choice analysis of major manufacturing industries, such opportunities are roughly non-existent in iron and steel and basic non-ferrous metals. Iron and steel and basic non-ferrous metals together account for more than one-half of the sector's gross energy consumption.

Electricity, gas and water (E-G-W)

- The demand for aggregate energy input in E-G-W is very own-price inelastic, less than 0.05 (in absolute terms) in 1998.
- However, there are some possibilities of switching between different fuels, especially between gas and oil and gas and coal.
- The corresponding sub-sector level analysis finds that this inter-fuel flexibility is largely in private electricity generation. The own-price elasticities of different fuels in private electricity generation are mostly quite large (in absolute terms). The switching possibilities between gas and coal are especially high.
- In public power generation, the inter-fuel substitution opportunities are much less. The cross-price elasticities between the gas-oil and gas-coal pairs are positively signed but insignificant at the 10 per cent level.

Other sectors

- The demand for aggregate energy in transport – the third largest energy consuming sector – is inelastic in relation to the price of energy; moreover, there are essentially no substitution possibilities for switching away from oil, the predominant fuel source, to other fuel sources.
- Like transport, the demand for aggregate energy in mining is very price inelastic. However, significant substitution opportunities are found between most fuel pairs, including gas-oil and gas-coal.
- Estimates of consumer energy demand conflict with each other. However, according to the elasticity estimates from recent data, gas and other fuels are strong substitutes, electricity and other fuels tend to be complements, whereas the cross-price elasticities between electricity and gas are insignificant, although positively signed.

Notes

[1] The Protocol involves legally binding GHG emission targets for the so-called developed countries as defined in the Annex I of the Protocol. More precisely, Annex B countries, including Australia, are collectively required to reduce their total GHG emissions to at least 5 per cent below 1990 levels in the first commitment period of 2008-12.

[2] According to Brown *et al.* (1999:5), GHG emissions, in CO_2-equivalent terms, are expected to increase by about 39 per cent between 1990 and 2010 in the business-as-usual scenario, growing at an average rate of 1.65 per cent a year.

[3] For instance, the emergence of a coal-fired power generation technology with a very high thermal efficiency.

[4] Energy conservation – defined typically as falling energy consumption to national income ratio – results from an interaction among economic forces such as income growth, the rate of technological progress and rising relative energy prices which induce substitution away from energy intensive activities (Weyman-Jones 1986:205). However, the analysis in this chapter focuses only on the substitution aspect, especially inter-fuel substitution possibilities. For an idea of the energy conservation potential on account of technical change see Section 6.4, Chapter 6.

[5] The oil shocks of the 1970s and the consequent recessions resulted in a decline in the demand for steel; the 1982 depression caused much higher reduction in the demand for steel.

[6] See Table 6.1 in Chapter 6.

[7] Crude oil is not included in total energy consumption in the industry.

[8] The corresponding estimate from Chapter 7 is not presented because of the concavity violations. The own-price elasticity of oil plotted in the figure is correctly signed and highly significant.

[9] The corresponding elasticities estimated in Chapter 7 are not reported due to a much higher incidence of the curvature violations.

[10] Coal is essentially wood, as coal also acts as a residual category.

9

Summary and conclusions

Synopsis

The thesis is summarised, chapter by chapter, beginning from the introductory chapter. The main contributions to the knowledge of economics in this thesis are briefly discussed. Limitations/weaknesses are reported and areas for future research are highlighted.

9.1 Introduction

The main objective in this research was to model energy demand by the residential, industrial and commercial sectors in Australia with a view to obtaining a comprehensive set of energy demand elasticities. The study employed the interrelated factor/commodity demand models, as energy demand by economic agents – households and firms – is not determined in an isolated setup. The consumer energy demand for different energy sources, for instance, was estimated using two different techniques. In the first case, the Almost Ideal (AI) demand system, parameterised both as an autoregressive error model and a vector error correction model (VECM), was used to obtain the energy demand elasticities characterising the residential sector. In the other case, the residential energy demand was estimated by applying the dynamic OLS (DOLS), developed by Stock and Watson (1993), to national-level quarterly data.

The demand for energy in aggregate and its components, along with that of other factor aggregates – labour, capital and materials – was specified using a dynamic factor demands model which explicitly recognises adjustment in quasi-fixed factors – capital, for instance – developed by Berndt *et al.* (1980). In a separate exercise, using the translog specification, the inter-fuel substitution opportunities were analysed at the maximum level of detail permitted by the data.

The study also included two economic applications. Using three different estimates of consumer energy demand elasticities, the residential energy demand, including electricity, gas and other fuels, and associated CO_2 emissions, were projected to 2010 under business-as-usual conditions and under a carbon tax regime. The other application quantified the deadweight loss of the carbon tax using, again, three different estimates of the consumer energy demand elasticities.

For the purposes of modelling energy demand, along with other factors/commodities, the economy was divided into eight sectors: agriculture; mining; manufacturing; transport and storage; electricity, gas and water; commercial; and residential. In a separate exercise, which aimed specifically at analysing the inter-fuel substitution possibilities in the industrial and commercial sectors, the two sectors were divided into 37 industries.

Energy consumption in each sector, with the exception of agriculture, construction and the residential sector, was divided into the consumption of electricity, gas, oil and coal. The residential energy consumption was divided into three categories: electricity, gas and a residual category. Expenditure on the residual category, which consists primarily of wood and fuel oil, is relatively small – only 8 per cent of total residential energy expenditure in 1998. For agriculture, only two fuels, electricity and oil, were considered, as the consumption of the other two fuels is very small. Finally, for the construction industry, coal consumption was dropped because of its negligible use.

The rest of this concluding chapter is organised as follows. Section 9.2 summarises the thesis, chapter by chapter, beginning from the introductory chapter. The main contributions of this research to the knowledge of economics are discussed in the next section. The limitations of this work are discussed in Section 9.4, which also includes a brief discussion on possible research extensions.

9.2 Summary

9.2.1 Chapter 1

The chapter began with a survey of the literature on greenhouse mitigation costs in Australia, covering studies based mostly on large-scale economic models of the national or global economy. The brief survey helped further highlight the significance of obtaining the estimates of energy demand structures for various industries/sectors, as the abatement cost results were found to depend critically on the estimates of energy demand parameters. The chapter then moved on to surveying the Australian literature on energy demand estimation, after referring briefly to the international literature on the subject.

In Australia the available literature on energy demand estimation, fuel substitutions with other factor aggregates/commodities and inter-fuel substitutions, is not only scant but also emerged predominantly in the distant past, in the 1970s to the mid 1980s. A large proportion of the studies focussed on electricity demand, using single equation methods. The system-based studies focussed mainly on the manufacturing sector using translog specification in most cases.

The chapter then moved on to reviewing the international literature on energy demand estimation with a view to selecting energy demand specification and estimation techniques for this research. The AI demand system, with a dynamic representation, and the DOLS were chosen for the analysis of consumer energy demand. For the investigation of the industrial and commercial energy demand, Berndt *et al.*'s (1980) dynamic demand system along with Fuss' (1977) two-stage optimisation procedure were selected. The chapter ended with an outline of the thesis.

9.2.2 Chapter 2

Chapter 2 illuminated the trends in the national energy sector, and in particular the trends in the fuel mix in the main energy consuming sectors. The subsequent econometric analysis investigated the substitution possibilities between the various fuels used and did not deduct the fuel produced from total fuel consumption; therefore, the focus was on gross energy consumption trends as opposed to net energy consumption trends. The chapter also presented trends in national greenhouse gas emissions. The national level annual data from 1974 to 1998 on energy consumption, and greenhouse gas emissions data from 1990 and 1997 were employed.

Gross national energy consumption in Australia increased from 3.1 exa joules in 1974 to 5.7 exa joules in 1998, growing at an average rate of 2.6 per cent a year. Nearly four-fifths of this additional energy, roughly 2.6 exa joules, was consumed during the 15 years 1983 to 1998 – a period of relatively stable energy prices. While the coal share remained relatively stable at around 43 per cent, the oil share fell from 42.1 per cent to less than 29 per cent during this period. Electricity and gas consumption, on the other hand, grew much faster, leading to significant improvements in their relative standing in the fuel mix. The electricity share, for instance, increased by a factor of 1.5 to 12.4 per cent while that of gas increased 2.4-fold to 15.3 per cent.

Three industries – manufacturing, electricity, gas and water and transport – dominated the energy sector, with a combined share of about 80 per cent. While the transport sector's share in gross national energy consumption remained relatively stable at around 22 per cent, the share of the power sector increased by 11.5 percentage points to above 35 per cent and that of manufacturing declined by 13 percentage points to 26 per cent in 1998.

The fuel mix in transport and power is overwhelmingly dominated by a single source; in transport more than 98 per cent of energy is sourced from oil, while coal accounts for about 88 per cent of gross energy consumption in the power sector. The energy mix in manufacturing is fairly diverse; coal is the main fuel source followed by gas, oil and electricity. Six manufacturing industries account for more than four-fifths of the manufacturing sector's total energy consumption. Indeed, two industries – iron and steel and basic non-ferrous metals – account for more than one-half of the sector's total energy consumption. Indeed, more than one-half of the manufacturing sector's total coal consumption is used in one industry, iron and steel.

The mining sector, with a share of 5 per cent in gross national energy consumption in 1998, experienced the fastest growth in energy consumption, 5 per cent a year. The commercial sector, a relatively small energy consuming sector, depends largely on electricity and gas. The residential sector accounts for less than 7 per cent of gross national energy consumption and depends mainly on electricity and gas.

Between 1990 and 1997, national greenhouse gas emissions increased by 11 per cent to 431.3 million tonnes, largely CO_2. The energy sector emissions, both from combustion and non-combustion sources, accounted for nearly four-fifths of national emissions in 1997.

9.2.3 Chapter 3

Chapter 3 studied the structure of consumer energy demand. The underlying consumer preferences were represented, as mentioned above, by the AI system. A dynamic structure, to account for the stickiness of the energy-using appliances, was added by formulating the AI model as a vector error correction model (VECM), which nests within it the stock adjustment and the autoregressive error models. The error correction model was applied to two different data sets. In one application, national-level quarterly data from the third quarter 1969 to the second quarter 1998 was employed. The other application used a panel of five states, New South Wales, Victoria, Queensland, Western Australia and South Australia, to estimate the consumer energy demand structure. All other household expenditure was introduced in these applications as another demand variable to close the system. As a consequence, the explanatory variables in the four-equation demand system were the four price indices and total (per capita) household consumption expenditure. Apart from the above-mentioned variables, three quarterly dummy variables were included in the set of regressors in the first of the two applications. The second application employed four state dummies in addition to the three quarterly dummy variables.

In another application, the AI model was parameterised as an autoregressive error model and estimated using national-level annual data from 1970 to 1998. The more general formulation of the error correction model was not considered due largely to the limited number of observations. Furthermore, the weak separability assumption was invoked which resulted in a three-equation fuel share system. The set of explanatory variables included three fuel price indices, total per capita household expenditure on energy and a trend variable to capture the impact of technical change on household fuel consumption.

For the purposes of estimation, the residual fuel expenditure share (non-energy expenditure share equation) was arbitrarily dropped from the autoregressive model (error correction model) and the remaining two (three) equations were estimated by employing a non-linear, iterative, seemingly unrelated regression procedure. Regression results and estimates of elasticities that correspond to the panel data based error correction model were not reported, as the parameters were largely insignificant and elasticity estimates mostly implausible. Instead, the corresponding static model results were presented. The underlying expenditure function frequently violated the curvature properties; however, the reported own-price elasticities, both Hicksian and Marshallian, possessed theoretically correct signs in all the cases.

The demand for electricity and other fuels was found to be considerably less (own) price sensitive in the panel data case. According to the other two models, the annual data based autoregressive error model and the vector error correction model, the own-price elasticities of the two fuels are at least twice as large (in absolute terms) as the panel elasticities. The gas demand elasticity is mostly insignificant though correctly signed in all cases. The demand for the three fuels was found to be significantly influenced by income, especially that of gas and other fuels.

According to the autoregressive error model, electricity, gas and other fuels tend to be net substitutes (the Hicksian cross-price elasticities are positive and significant in two-thirds of the cases) but gross complements (the Marshallian cross-price elasticities are largely negative). The analysis based on national-level quarterly data, in contrast, found significant substitution possibilities, net and gross, between electricity and residual fuels and between gas and residual fuels. However, contrary to expectations, the regression results suggested that Australian households consume electricity and gas in a complementary fashion. The panel data-based analysis, on the other hand, found significant substitution possibilities between gas and other fuels only. The cross-price elasticities between electricity and gas are positive but not significant.

Failure to find theoretically correct signs of some of the inter-fuel substitution elasticities, especially in the case of panel data where 280 observations were employed, appears to be largely attributable to insufficient price variation. During the past 14 years, relative fuel prices have had little variation and real fuel prices have generally declined. In fact, variations in household energy demand during this period, are primarily explained by the state-specific factors and temperature variations. Prices and income have played a very minor role. Fuel prices, especially of residual fuels, changed markedly during the late 1970s and early 1980s but the electricity/gas price ratio remained quite stable which, in combination with the gas supply constraints, most probably, resulted in the wrong signs for the national-level quarterly data-based cross-price elasticities between electricity and gas. However, before drawing any conclusions, it seemed appropriate to test the robustness of elasticity estimates using different functional specifications. This question was the subject matter of the next chapter.

9.2.4 Chapter 4

In the first part of Chapter 4 the DOLS, developed by Stock and Watson (1993), was also used to model consumer energy demand covering electricity, gas and other fuels. This was done essentially to obtain a second opinion on the inter-fuel substitution relationships. The statistical evidence in the previous chapter was largely in favour of a complementarity relationship in electricity and gas use, which is difficult to justify, as the two fuels are considered to be good substitutes in the areas of cooking and space and water heating.

The DOLS – a single equation approach and thus much less attractive from a theoretical point of view – was chosen as it allows much more flexibility in terms of specifying dynamics. Long-run or equilibrium per person demand for a particular fuel was assumed to depend on the (own) price of that fuel, prices of the two other fuels, real per capita income and the state of the weather. The study used national-level quarterly data for the period from the third quarter 1969 to the second quarter 1998 – a total of 116 data points. The state of weather was represented by quarterly dummy variables.

Exact specification of a DOLS equation depends crucially on the integration properties of individual variables. A prior examination of the variables detected the presence of a structural break, associated with the oil shock of 1978, in roughly all time series. The unit root analysis, which took into account the shock, found all variables to be integrated of order one, except the price of the residual fuels which was found to be level stationary. Furthermore, the application of Johansen and Juselius procedures, the trace test and the maximum eigenvalue test, rejected the null hypotheses of no long-term relationship in each of three fuel demand equations. Rather, the analysis suggested the presence of a unique co-integrating vector in each case.

Demand for the three energy categories is fairly (own) price responsive, as the null of unit elastic demand is not rejected in either case. In sharp contrast to the VECM-based estimates in the previous chapter, electricity and gas are strong substitutes; interestingly, the demand for gas is more sensitive to electricity price variations than to gas price changes. Also, electricity and residual fuels are necessities, whereas gas is a luxury. There is, however, one sticking point in this set of results. The cross elasticity of gas demand with respect to the residual fuel price is negative, although the cross-price elasticity of residual fuels demand with respect to gas price is positive and significant.

In the second part of the chapter, the estimates of energy demand elasticities were used to project consumer energy demand for individual fuels and associated CO_2 emissions under two alternative scenarios. In the first case it was assumed that fuel prices, the average consumer price level, per capita income and population growth over the projection period, 2000 to 2010, would be at the trend rate of 1989 to 1998. The other scenario gradually imposed a tax per tonne of CO_2 on each fuel, gradually increasing to $300 per tonne of carbon in 2010. Meanwhile, fuel prices increased at a constant proportionate rate such that each price reflects the total amount of the tax in 2010. Income and the general price level in this alternative scenario were assumed to be unaffected under the assumption that the tax revenue thus collected is used to reduce payroll taxes.

In addition to the DOLS elasticities, this chapter considered two other sets of energy demand elasticities, estimated in the previous chapter, with a view to projecting energy demand and emissions. The first set of elasticities was obtained by expressing the AI model as a vector error correction model. The other set was obtained by applying the static AI (S-AI) model to a panel data set comprising five states: New South Wales, Victoria, Queensland, South Australia, and Western Australia.

The estimated growth rate of total energy consumption and emissions in the baseline case ranges between 1.06 per cent and 1.39 per cent. Significant disparities are found as far as growth rates of individual fuels are concerned. Demand for residual fuels is expected to increase at a rate higher than that of total energy use whereas gas demand is estimated to fall. Demand for electricity, in contrast, is estimated to grow at roughly the rate of population growth. These growth differentials are largely explained by the corresponding fuel price inflation differentials.

The growth rates of total energy consumption and emissions are estimated to fall to around 0.6 per cent per annum in the case of DOLS and S-AI but to -0.3 per cent from 1.06 per cent in the case of the VECM representation. The relatively greater abatement in the case of the VECM representation, however, is not credible as this model found significant complementarity between electricity and gas. The growth rates of electricity and residual fuels demand and emissions are predicted to fall relative to the baseline scenario across the three estimators, but the behaviour of gas is not consistent across estimators largely because of differences in the estimates of cross-fuel price elasticities.

9.2.5 Chapter 5

The deadweight loss of a carbon tax was investigated in Chapter 5 using the estimated consumer energy demand parameters. In order to analyse welfare implications of a tax structure, it is crucial that the underlying expenditure function be quasi-concave. However, in the previous estimates of consumer energy demand parameters in Chapter 3, the Slutsky Matrix (SM) frequently failed to satisfy the conditions of negative semidefiniteness. Therefore, the AI demand system covering electricity, gas, other fuels and non-fuel household consumption expenditure was re-estimated after incorporating local curvature conditions with a view to analysing the deadweight loss of a carbon tax.

The curvature-restricted AI methodology was applied to three data sets: 1) national-level annual data from 1970 to 1998; 2) national-level quarterly data from the third quarter 1969 to the second quarter 1998, and 3) state-level quarterly data on five states spanning the period from the third quarter 1984 to the second quarter 1998. The panel data comprised New South Wales, Victoria, Queensland, South Australia and Western Australia.

In the case of the annual data set, the curvature restrictions were imposed at 1998 and at the fourth quarter 1997 for the corresponding quarterly specification. The underlying expenditure function for the panel data specification was restricted to be concave in prices in the neighbourhood of the fourth quarter 1997, and corresponding to Western Australia. For the annual data, the expenditure function was found to be concave over the entire sampled period, although some curvature violations were noted for the other two specifications.

In analysing the welfare implications of a carbon tax of $300, it was assumed that the production activity was characterised by constant marginal cost conditions and therefore, perfectly elastic supply curves. As a result of this full pass-through assumption, the carbon tax of $300 was estimated to increase the price of electricity, gas and other fuels by 72 per cent, 53 per cent and 88 per cent, respectively. It was assumed, for the sake of convenience, that the carbon tax would leave incomes and the general price level unaffected under the assumption that the carbon tax revenue would be recycled in the form of a pay-roll tax deduction.

The annual model found electricity-gas and electricity-other fuels to be substitutes, while gas and other fuels were complements. The national-level quarterly specification, by contrast, showed complementarity between electricity and gas. The other fuel pairs, electricity-gas and gas-other fuels, were substitutes. The fuel cross-price elasticities for the panel data were typically very small (in absolute terms) in relation to the corresponding national-level estimates. However, the cross-price elasticity between electricity and other fuels was negative whereas the other cross-price sensitivities were positive.

The demand for other fuels is the most (own) price responsive across the three data sets, followed by electricity in the two annual data specifications and by gas in the state-level model. Gas demand is particularly price responsive in Victoria, where the gas demand elasticity was estimated to vary between -0.73 and -0.80.

Using annual data, a tax of $300 per tonne of carbon was estimated to result in a deadweight loss of $495 million, roughly 7 per cent of total household fuel expenditure. For the corresponding national-level quarterly specification, the net welfare loss fell 2.7 per cent to $482 million and to $434 million for the state-level panel data based demand parameters.

9.2.6 Chapter 6

Chapter 6 specifically examined the inter-fuel substitution opportunities in the industrial and commercial sectors, while ignoring substitutions in aggregate factors. The two sectors were divided into 37 industries while total energy consumption in each industry, with the exception of a few industries, was divided into electricity, gas, oil and coal. In order to investigate the inter-fuel substitution structure, the production structure of an industry was assumed to be weakly separable in the factor aggregates, which, in turn, were assumed to be homothetic in their components. This crucial two-step assumption helped analyse the fuel choice problem in isolation, without worrying about the aggregate choice.

The underlying unit energy cost function, specified in terms of the prices of the four fuels – electricity, gas, oil and coal – and a time trend, was represented by the linearly homogenous translog specification. The trend variable was included in the set of regressors with a view to capturing the fuel efficiency biases, if any, of changing technology. The resulting fuel cost share system was estimated for each of the 37 industries using national-level annual time series data spanning from 1974 to 1995. Due to the singularity of the system, the coal share equation was arbitrarily dropped and the remaining three-equation system was estimated in SHAZAM using the non-linear iterative seemingly unrelated regression procedure of Zellner.

However, the underlying cost function frequently violated the curvature conditions in most industries. Autocorrelation was another problem encountered at the estimation stage, as in a typical equation the DW statistic was less than unity. The curvature problem was, however, of a more serious nature, as in many cases own-price elasticities of different fuel sources were incorrectly signed. Local as opposed to global concavity restrictions were imposed on the underlying matrix of second-order partial derivatives of the cost function, which led to a generally well-behaved cost function, without significantly trimming flexibility. The autocorrelation problem was, however, not addressed partly because of the complication caused by the concavity restrictions and partly because of the small number of observations.

Technical change is electricity-using but oil-saving in most industries, with only a few exceptions. The direction of bias is less obvious in the other two fuels although, on average, it is positive for gas and negative for coal. Technical change is coal-saving in the iron and steel industry which is the single largest user of coal within manufacturing, employing more than one-half of all coal consumed in the sector. However, technical change has enhanced the consumption of coal in the public electricity generation sub-sector, which is the single largest user of coal across all industries.

Electricity demand is (own) price inelastic. In nearly half of the industries the elasticity is less than 0.25 (in absolute terms). Further, in almost two-thirds of the industries it is less than one-half. The demand for the other three fuels – gas, oil and coal – is not only more price sensitive but also the sensitivity varies greatly across industries. This is particularly true for oil, where, in nearly 40 per cent of industries the elasticity exceeds unity. The coal demand elasticity in the iron and steel industry, however, is essentially zero and in public electricity generation it is -0.14.

There is some evidence of complementarity in fuel use, especially in the case of the coal-oil and coal-electricity pairs. The dominant feature characterising most industries is, however, substitutability between fuels, especially in the case of gas-oil and gas-electricity. In both public and private electricity generation sub-sectors, gas and coal tend to be substitutes.

9.2.7 Chapter 7

In Chapter 6 total energy demand by industry was taken to be exogenous, as at the level of detail sought in that analysis, data on other factor aggregates – capital, labour, and non-energy materials – and output could not be obtained. However, in order to obtain estimates of the demand elasticity of energy in aggregate and the substitution elasticities between energy and other factor aggregates, it is crucial to endogenise total energy demand along with that of the other inputs. This issue was tackled in this chapter by compromising at the level of industrial detail.

The demand for interrelated aggregate factors and the four fuel sources was specified using a dynamic model of factor demands that is based explicitly on dynamic economic optimisation principles (Berndt *et al.* 1980). Capital stock, treated as a quasi-fixed factor, was assumed to be subject to quadratic adjustment costs, resulting from internal disruptions within the firm. To this end, the non-residential sector economy was divided into seven sectors: agriculture; mining; manufacturing; construction; electricity, gas and water; transport, storage and communications; and services.

The production structure of each industry, specified in terms of energy, non-energy materials, labour and capital, was approximated by a quadratic cost function. The corresponding fuel structure, specified in terms of electricity, gas, oil and coal, was represented by a homothetic, linearly homogenous, translog cost function. The two models, the aggregate choice model and the fuel choice model, were estimated separately for each of the seven industries using national-level annual time series data for the period 1974 to 1998. For mining, electricity, gas and water, transport and service industries, output and material price deflators were not available. As a result, the assumption of weak separability between non-energy materials and other factors was invoked for the four industries.

Local curvature conditions for 1998 were imposed on both cost functions due to frequent curvature violations. The resulting cost functions were generally well-behaved and not just at the concavity point. The aggregate choice model was also treated for serially correlated errors, using a diagonal autocovariance matrix. The fuel choice model was not corrected for the problem, despite symptoms, primarily because of implausible elasticities resulting from the dual treatment.

Energy and labour are substitutes, both in the short and long-run, in most industries, whereas energy and capital are long-run complements in all industries, indicating that a carbon tax will diminish labour productivity and may slow down economic growth by retarding investment. Capital and labour, on the other hand, are long-run substitutes in five industries. In manufacturing and construction industries, however, the elasticity of labour with respect to capital is negative, whereas the elasticity of capital with respect to labour is positive.

The demand for energy in aggregate is not very (own) price sensitive, even in the long-run. Indeed, in five industries the energy own-price elasticity in the long-run is less than 0.1 (in absolute terms). In the remaining two industries, manufacturing and construction, it is around -0.6. The difference between the short and long-run energy demand elasticities is very small, except for manufacturing in which the long-run energy demand elasticity is twice as large as the corresponding short-run elasticity.

In agriculture, a relatively minor energy consuming sector, the demand for energy is not only independent of own-price but also no substitution possibilities are found between electricity and oil, the two main fuels used by the sector. In other industries the inter-fuel price sensitivities are significant, especially in manufacturing, electricity, gas and water and services. For instance, significant substitution possibilities from oil and coal to gas exist in the manufacturing and electricity, gas and water industries which together use more than 60 per cent of gross national energy.

Generally, electricity demand is the most price inelastic; the own inter-fuel price elasticity of the fuel is less than 0.08 (absolute terms) in all except two industries – construction and manufacturing. Gas, in contrast, is the most elastic of all fuels; in five industries the own inter-fuel price elasticity of the fuel exceeds 0.2 (in absolute terms) and within those five industries the elasticity exceeds 0.7 in three cases.

Complementarity in fuel consumption was found in some industries, especially in the case of electricity-oil (mining, electricity, gas and water, and construction), oil-coal (manufacturing, electricity, gas and water, services) and gas-coal (mining, services). The dominant feature characterising inter-fuel relationships, however, was substitutability.

9.2.8 Chapter 8

The previous two chapters modelled the structure of energy demand in the industrial and commercial sectors using flexible and/or dynamic demand systems. Earlier, in Chapters 3 and 4, consumer preferences were modelled with a view to explaining energy use behaviour in the household sector. The estimated energy demand structure, especially in Chapters 6 and 7, could only be overviewed due to the enormous number of parameters involved. However, in order to identify the energy substitution potential in various industries/sectors, a closer look at these structures was required.

Keeping this in mind, the aim of Chapter 8 was to further investigate the energy demand structures estimated in the thesis with a view to identifying the energy substitution potential, including inter-fuel substitution possibilities, in different industries/sectors. For this purpose, major energy consuming sectors namely manufacturing, electricity, gas and water, transport, storage and communication, mining and residential – with combined shares of total energy consumption of more than 94 per cent in 1998 – were chosen. Within manufacturing, attention was focussed on six major energy-using industries: iron and steel, basic non-ferrous metals, petroleum refining, basic chemicals, wood, paper and printing, and cement, lime, plaster and concrete. Similarly, in the electricity, gas and water sector, private and public electricity generation sub-sectors were further investigated to pinpoint such opportunities.

To this end, a two-step procedure, where applicable, was adopted. At the first stage, the energy substitution potential was explored at the sector level – for instance, manufacturing, electricity, gas and water – by employing the energy demand structure estimated using the dynamic factor demands model of Chapter 7. At the second stage, the sub-sector level estimates of fuel structure were brought into the discussion. This detailed treatment helped not only pin down the inter-fuel opportunities but also played a crucial role in determining whether the sector level estimates of inter-fuel substitutions were not distorted because of aggregation across a heterogeneous set of industries.

The aggregate analysis found significant energy substitution potential in the manufacturing sector. The demand for energy in aggregate is considerably own-price sensitive; as well, the inter-fuel price elasticities are fairly high (in absolute terms). The cross-price elasticities of gas demand show significant opportunities for substitution from oil and coal to gas.

The fuel choice analysis of iron and steel – the single largest energy-using industry in manufacturing with a share of about 29 per cent (87 per cent of which is coal) – found very limited inter-fuel substitution potential, especially from coal to gas (the second largest fuel source in the industry). In basic non-ferrous metals – the second largest energy-using manufacturing industry with a share of more than 20 per cent – the own-price elasticities showed considerable flexibility. However, gas-oil and gas-coal tend to be in complementary relationships.

Gas and oil are strong substitutes in the basic chemicals industry which meets more than 90 per cent of its energy requirements from the two fuels. In petroleum refining, there is little possibility of replacing oil – the main fuel source with a share of about 87 per cent in 1995 – with other fuels, as oil demand is nearly independent of its own-price movements. Strong inter-fuel substitution opportunities were found in the wood, paper and printing industry – which employs less than 5 per cent of the sector's gross energy consumption, especially from oil and coal to gas. In the cement, lime, plaster and concrete industry, gas and coal – the two main fuels, accounting for more than 80 per cent of total fuel use in the industry – tend to be complements.

Given the limited substitution potential in major energy-using industries, such as iron and steel and basic non-ferrous metals, it is probably the case that the aggregate analysis exaggerated the underlying inter-fuel substitution potential in the sector. Iron and steel and basic non-ferrous metals together account for more than one-half of the sector's gross energy consumption.

As far as other sectors are concerned, the demand for aggregate energy input in electricity, gas and water is very own-price inelastic, less than 0.05 (in absolute terms). However, there are some possibilities of switching between different fuels, especially between gas and oil and gas and coal. The corresponding sub-sector level analysis found that this inter-fuel flexibility was largely in private electricity generation. The own-price elasticities of different fuels in private electricity generation are mostly quite large (in absolute terms). The switching possibilities between gas and coal are especially high. In public power generation, the inter-fuel substitution opportunities are much less. The cross-price elasticities between the gas-oil and gas-coal pairs are positively signed but insignificant even at the 10 per cent level.

The demand for aggregate energy in transport – the third largest energy consuming sector – is inelastic in relation to energy prices; moreover, there are essentially no substitution possibilities for switching away from oil, the predominant fuel source, to other fuel sources. Like transport, the demand for aggregate energy in mining is very price inelastic. However, significant substitution opportunities are found between most fuel pairs, including gas-oil and gas-coal. Estimates of consumer energy demand conflict with each other. However, according to the elasticity estimates from recent data, gas and other fuels are strong substitutes, electricity and other fuels tend to be complements, whereas the cross-price elasticities between electricity and gas are insignificant, although positively signed.

9.3 Contributions

The main contribution to the knowledge of economics has been the estimation of a comprehensive set of energy demand elasticities characterising the residential, industrial and commercial sectors. As far as the residential sector is concerned, using different functional specifications and modern time-series methods, eight different estimates of the energy demand structure were obtained. Previously, the residential energy demand was studied in the 1970s and early 1980s using largely single-equation methods. The estimated energy demand parameters were used to analyse the welfare implications of a carbon tax. To the best of this author's knowledge, no study has analysed the welfare implications of a carbon tax in Australia using flexible system-based parameters.

In chapter 6, the first chapter on the estimation of non-residential energy demand elasticities, the commercial and industrial sectors were divided into 37 industries. Using national-level annual data and a translog cost function specification, the inter-fuel substitution elasticities and fuel efficiency biases of technical change involving electricity, gas, oil and coal were computed. The study also estimated the fuel efficiency biases for each of the 37 industries. This much-detailed analysis of the inter-fuel substitution structures has definitely not been published for the Australian economy and not, to the best of this author's knowledge, for other major industrialsed nations.

A dynamic demand system that is explicitly based on dynamic optimisation principles has been applied in this research for the first time in the case of the Australian economy. In this analysis, the entire non-residential economy was covered by dividing it into seven sectors. Both aggregate energy use and the fuel structure was modelled for each of the seven sectors. Previous Australian studies on the subject typically looked at one sector or a number of manufacturing industries using mainly the static translog model.

Under the Kyoto obligation, Australia may have to cut its greenhouse emissions by more than one-fifth in 2010, which will involve a reduction in energy demand by various sectors and a switching from more carbon intensive fuels to less carbon intensive fuels. The energy demand analysis in Chapter 8 is likely to be an essential ingredient of a greenhouse gas policy that intends to achieve this target. In that research, the energy demand parameters estimated in various parts of the thesis were integrated to identify the energy substitution potentials, including inter-fuel substitution opportunities, in different industries/sectors.

9.4 Limitations/future research

The main weakness of the energy demand analysis carried out in this research has been the treatment or, for that matter, non-treatment of the serial correlation problem. While estimating the inter-fuel substitution opportunities for the commercial and industrial sectors, two statistical problems were experienced: quasi-concavity violation and serial correlation. Curvature violation was a more serious problem in the sense that own-price elasticities were wrongly signed in many cases.

In order to take care of the concavity problem, local curvature conditions were incorporated that further fed the serial correlation problem. A diagonal autocovariance matrix was incorporated along with the curvature restrictions to account for the twin problems of concavity violations and autocorrelation. This did not improve DW statistics in most cases which is understandable as singularity of the system further restricts the autocorrelation structure to an identical ρ, autocorrelation coefficient, across all equations of an industry/sector. A general autocovariance matrix was not considered because of the small number of observations, and the complex and highly non-linear parameter structure that results from such a specification.

However, this combined treatment resulted in elasticity estimates which were implausibly large or small (in absolute terms), indicating that probably too much was being asked – in estimating both short and log-run parameters at the same time – from a small data set (22 data points in Chapter 6 and 25 data points in Chapter 7). It is assumed that the estimated relationships are not spurious that is, there exists a co-integrating vector in each case. It is fair to say that the fuel choice elasticity estimates should be qualified in the light of this statistical problem.

Although the problem of concavity violations is currently being researched (Moschini 1998, 1999; Ryan and Wales 1998, 1999, 2000), the approach being followed is flawed in the sense that it examines the problem in isolation. However, as seen in the present case, more than one problem can arise at the same time, making the job of a researcher much more challenging. The future research in this area should aim at devising methods that are more robust and can be employed in a variety of situations.

While estimating consumer energy demand elasticities in Chapters 3 and 4, the dependence of energy demand on the stock of energy-using appliances was modelled in an implicit fashion, due largely to the non-availability of adequate data on the stock of energy using appliances. However, an implicit treatment of dynamics is not without limitations. As Berndt *et al.* (1981) argue, it is not known what exactly is changing when the capital stock variable(s) is not modelled explicitly. Although in this research only the long-run elasticities were estimated for the residential sector, it may be the case that estimated parameters are distorted due to this implicit treatment. Future research on the subject should aim at explicitly incorporating the stock of durable energy appliances in consumer energy demand modelling.

A useful extension of this work could also be to use the estimated energy demand models for energy demand forecasts. Such information is crucial for cost-effective planning of energy production capacity. This is especially true for electricity because of the prolonged period of gestation of electricity plants and also due to the fact that costs of over capacity or under capacity are significantly large. Electricity demand forecasts based on econometrically estimated electricity demand models can help greatly reduce the chances of building a sub-optimal capacity. Similarly, the efficiency of investment in gas infrastructure depends crucially on reliable gas demand forecasts.

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